THEORY OF STRANGE MESONS AND BARYONS

MAXIM MAI

University of Bonn | The George Washington University

Heisenberg-Programm

DFG Deutsche Forschungsgemeinschaft

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STRONG 2020

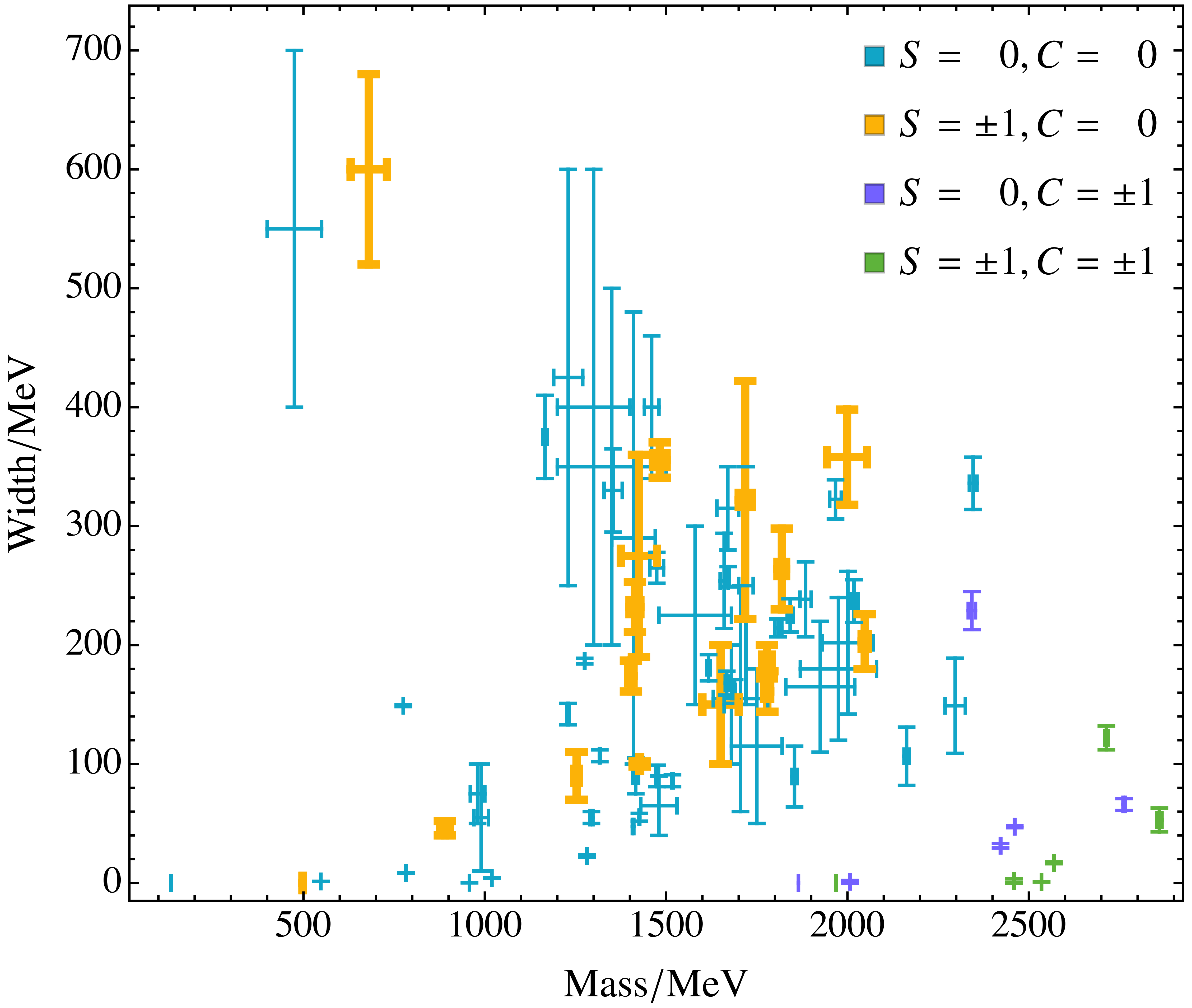
HADRON SPECTRUM — EXPERIMENT

Mostly excited states[1] ≈ 100 mesons

- intermediate energy regime
  - many overlapping (unflavoured) states
  - clearer picture through strangeness mesons (?)
- key questions

 *"what is the pattern of these states?"*

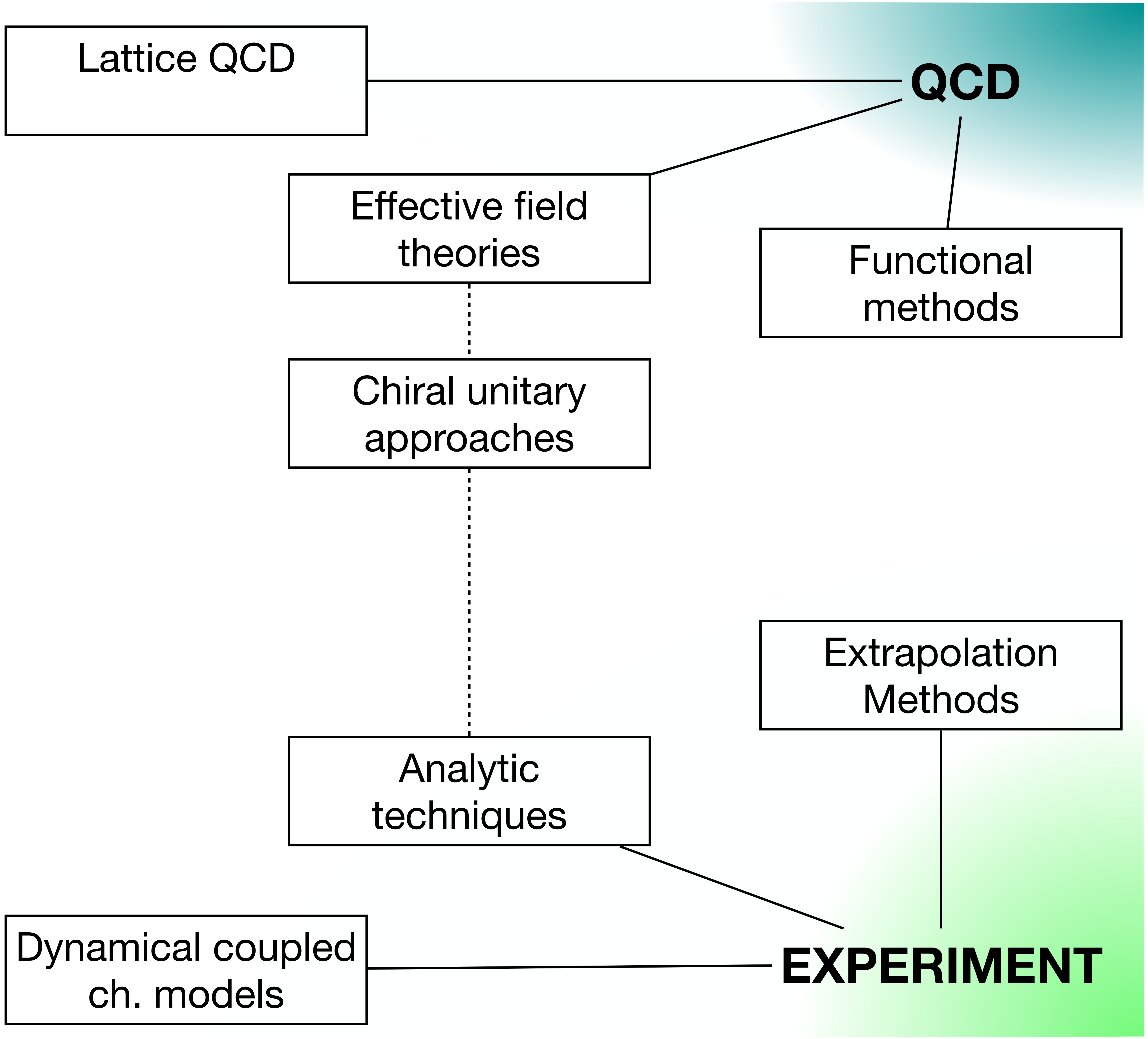
 *"how are they formed?"*



[FIG] MM, data from PDGlive 2024

Many theoretical approaches

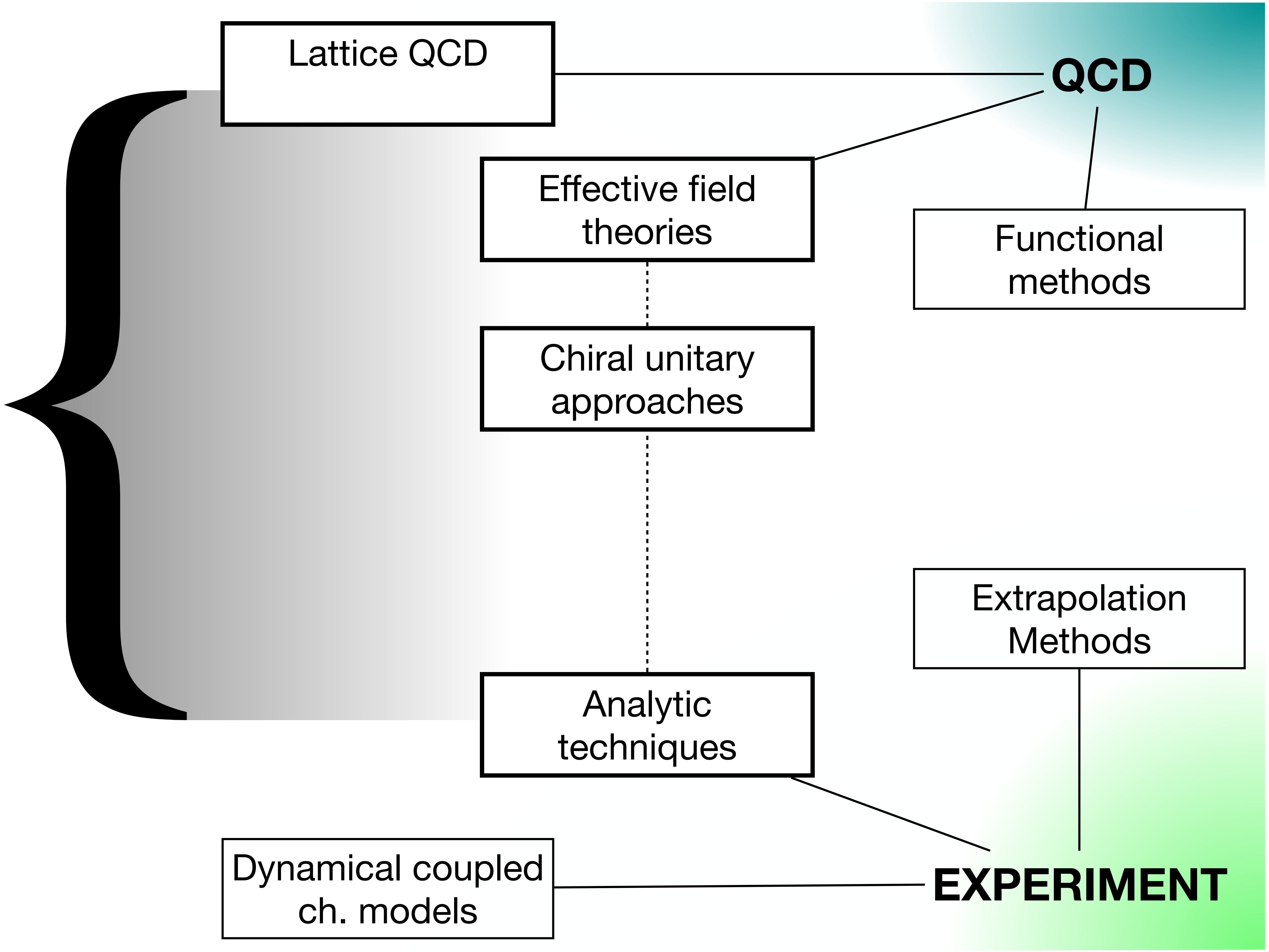
- varying degree of rigour (#QCD)
- varying ability of data description (#Experiment)
- birds vs. frogs



HADRON SPECTRUM — THEORY

This talk

- universal parameters of resonances
- from QCD to experiment and back
- cross-channel studies

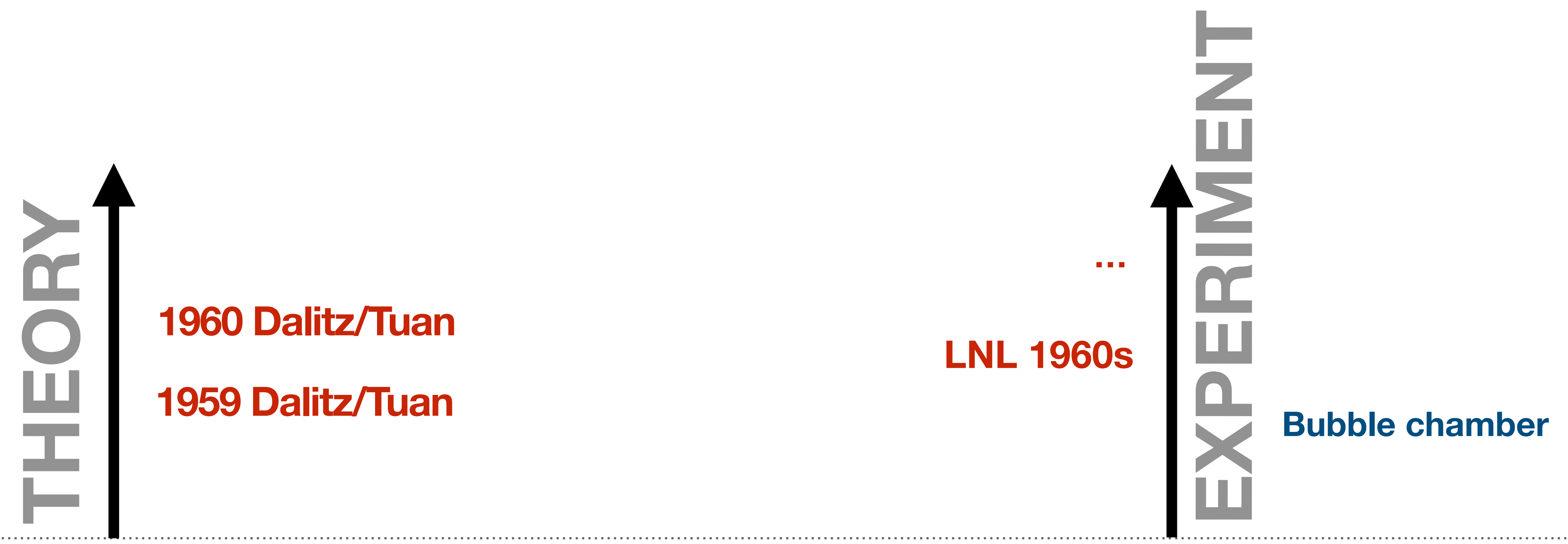


$\Lambda(1405)$ — A CURIOUS CASE OF A STRANGENESS RESONANCE

- **MM *Eur.Phys.J.ST* 230 (2021) 6, 1593-1607**
- J.-X. Lu, L.-S. Geng, MM, M.Döring [Phys.Rev.Lett. 130 (2023) 7]
- *F-K Guo, Y. Kamyia, MM, Ulf-G. Meißner [Phys.Lett.B* 846 (2023) 138264]
- D. Sadasivan et al. *Front.Phys.* 11 (2023) 1139236
- Pittler/MM, Vonk/MM in progress

STRANGENESS PROGRAMM

*“There is a **large experimental program on production of S particles** by nuclear collisions and by photons, scattering, and interactions of those mesons with nuclei, etc. But just between us theoretical physicists: **What do we do with all these data? We can’t do anything. …**”*
R. P. FEYNMAN



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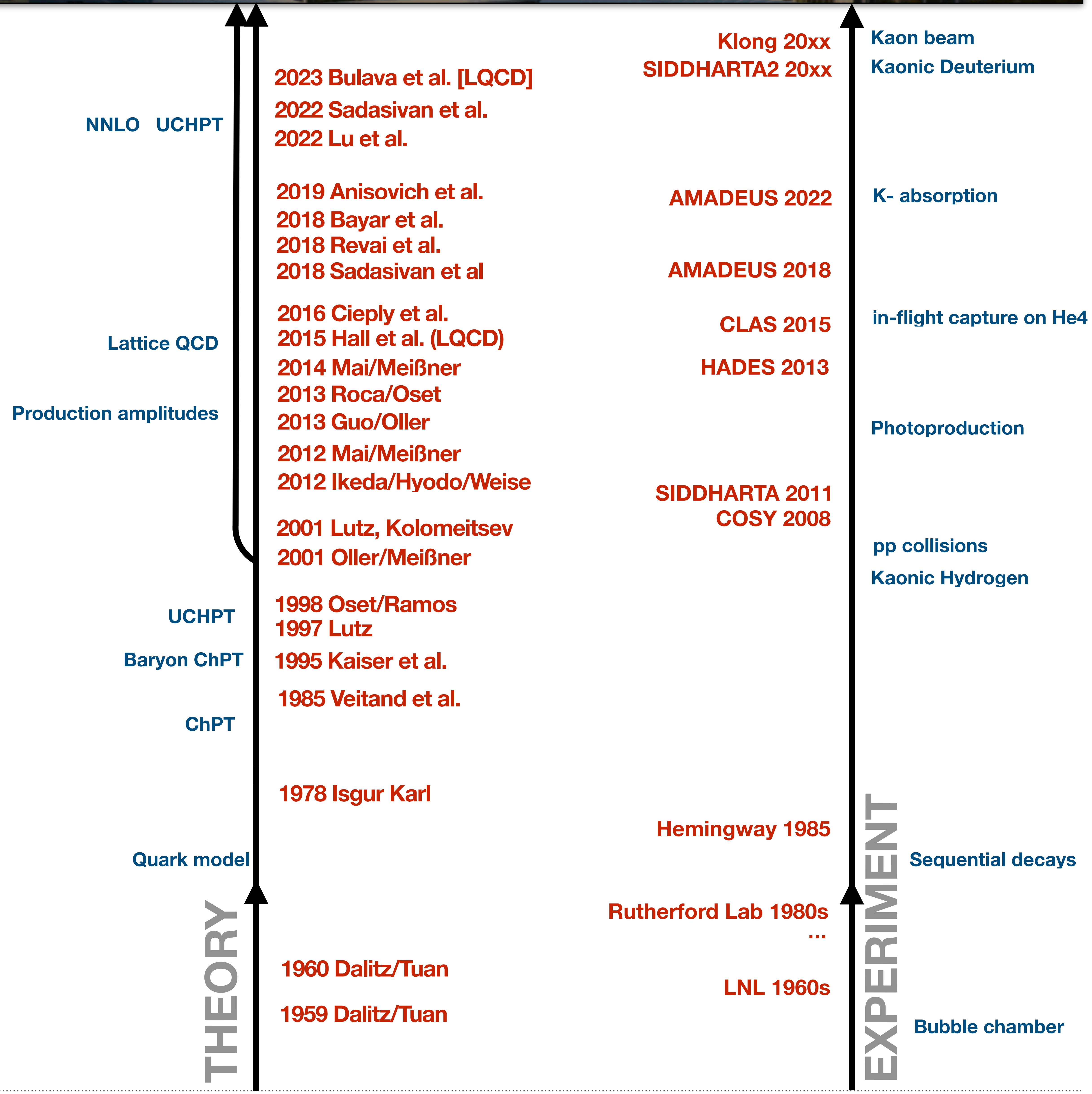

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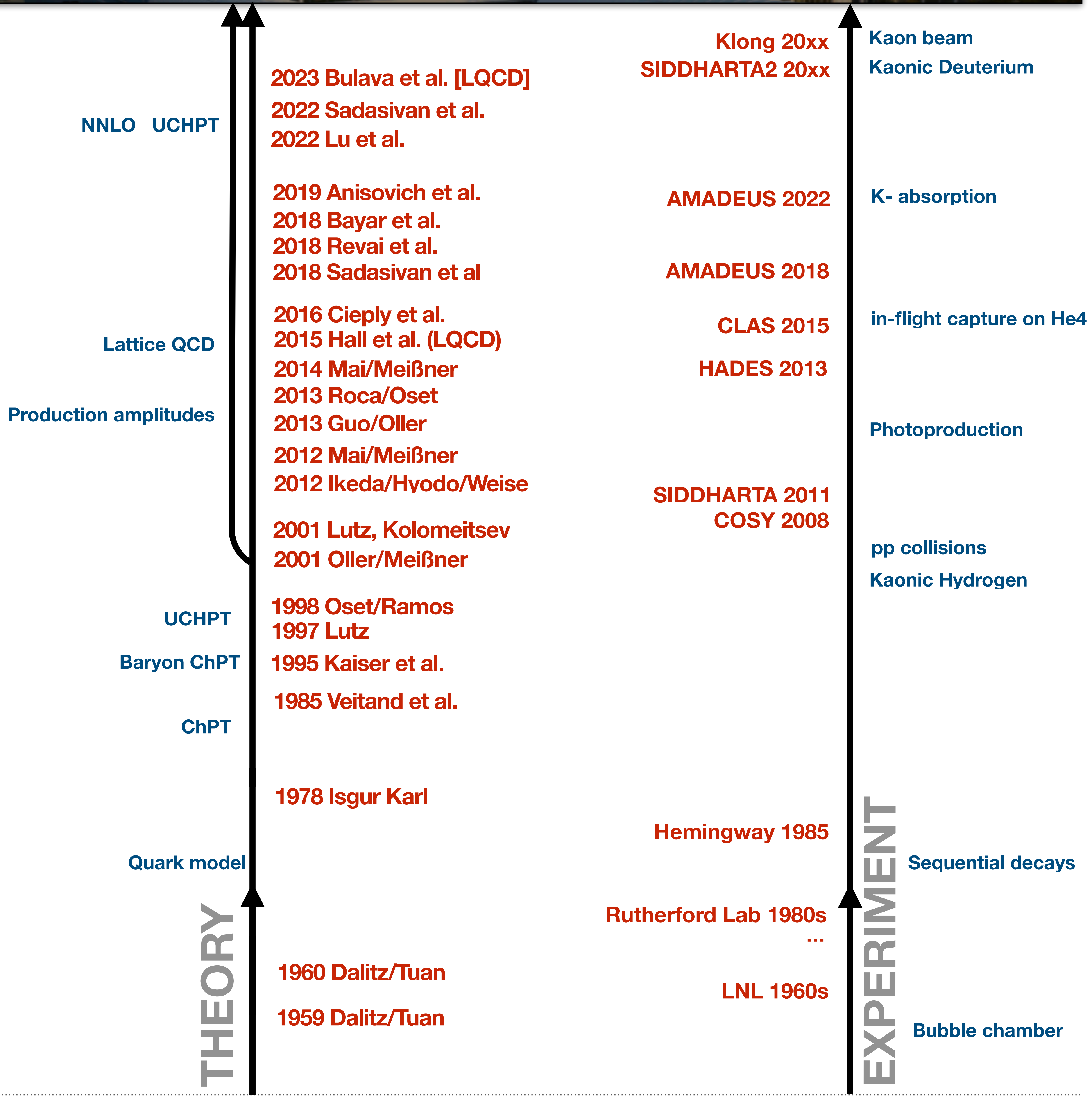
NEW STRANGENESS RESONANCES

- Sub-($\bar{K}N$)-threshold $\Lambda(1405)$ resonance
  - second state $\Lambda(1380)$ predicted from UCHPT
  - no direct experimental verification
  - confirmed by many critical tests / LQCD



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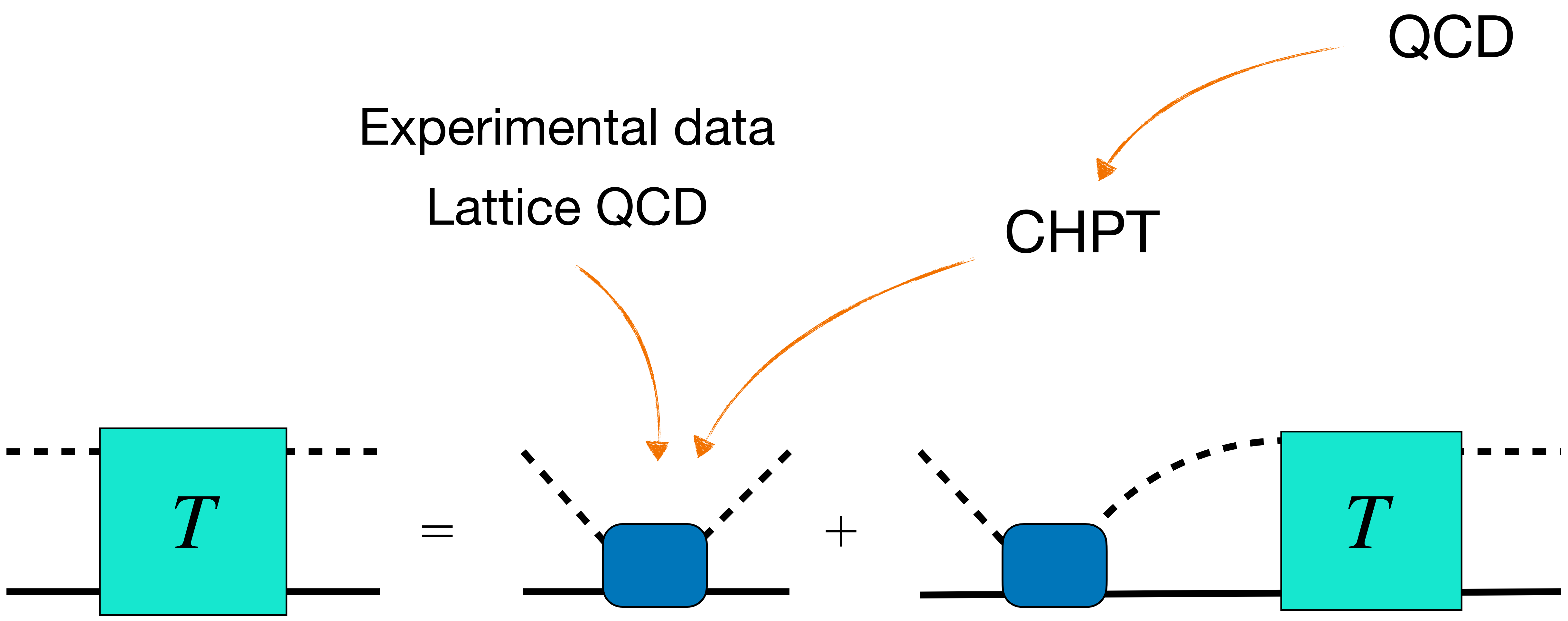
UNIVERSAL PARAMETERS

Transition amplitude — chiral unitary approach[1]

Chiral Perturbation Theory (#QCD#EFT)

form of the interaction at low energies



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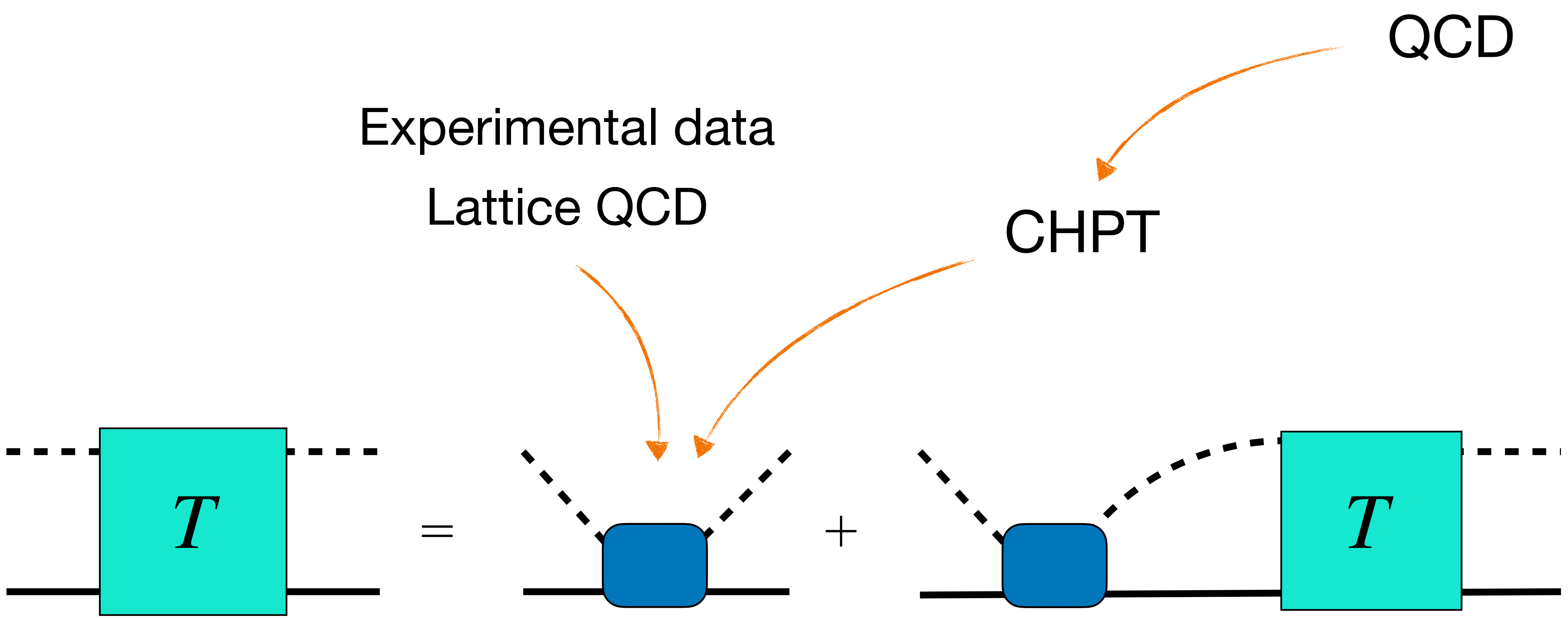

Unitary amplitude from the Bethe-Salpeter equation

(Fit free parameters to experimental data or LQCD)

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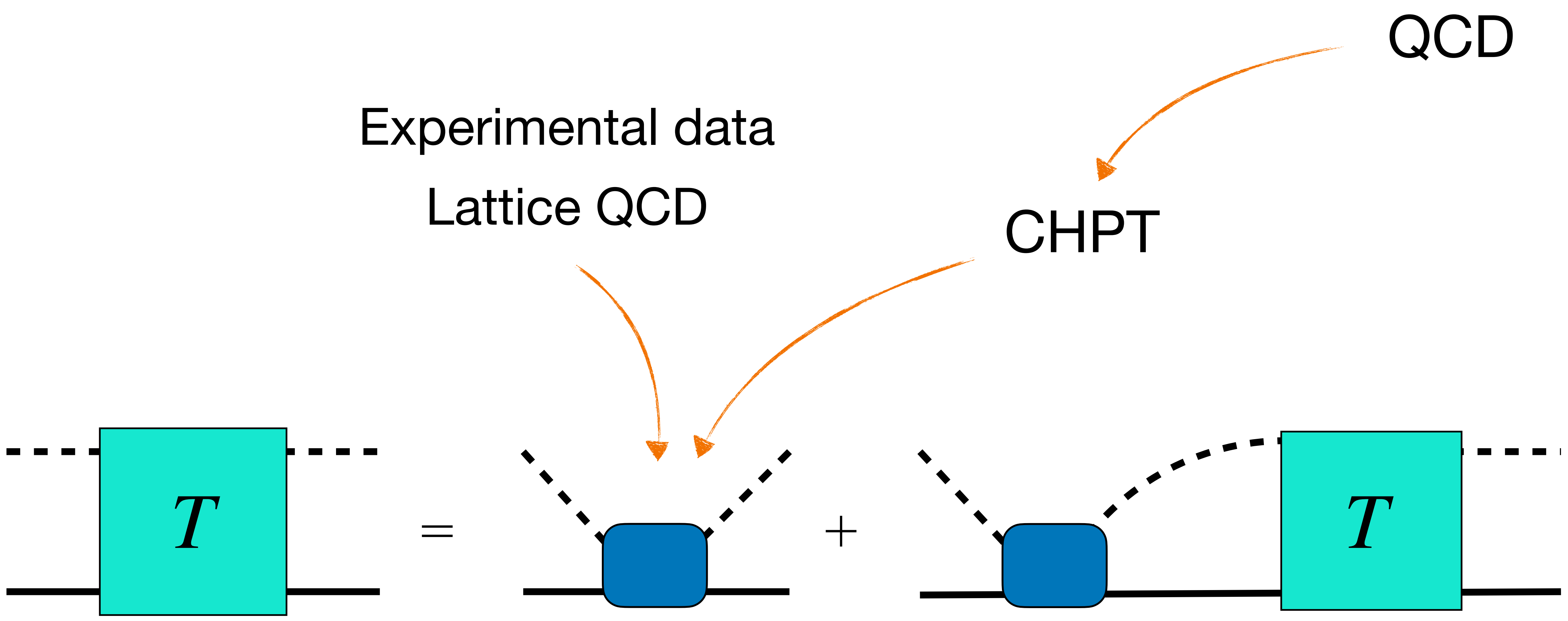

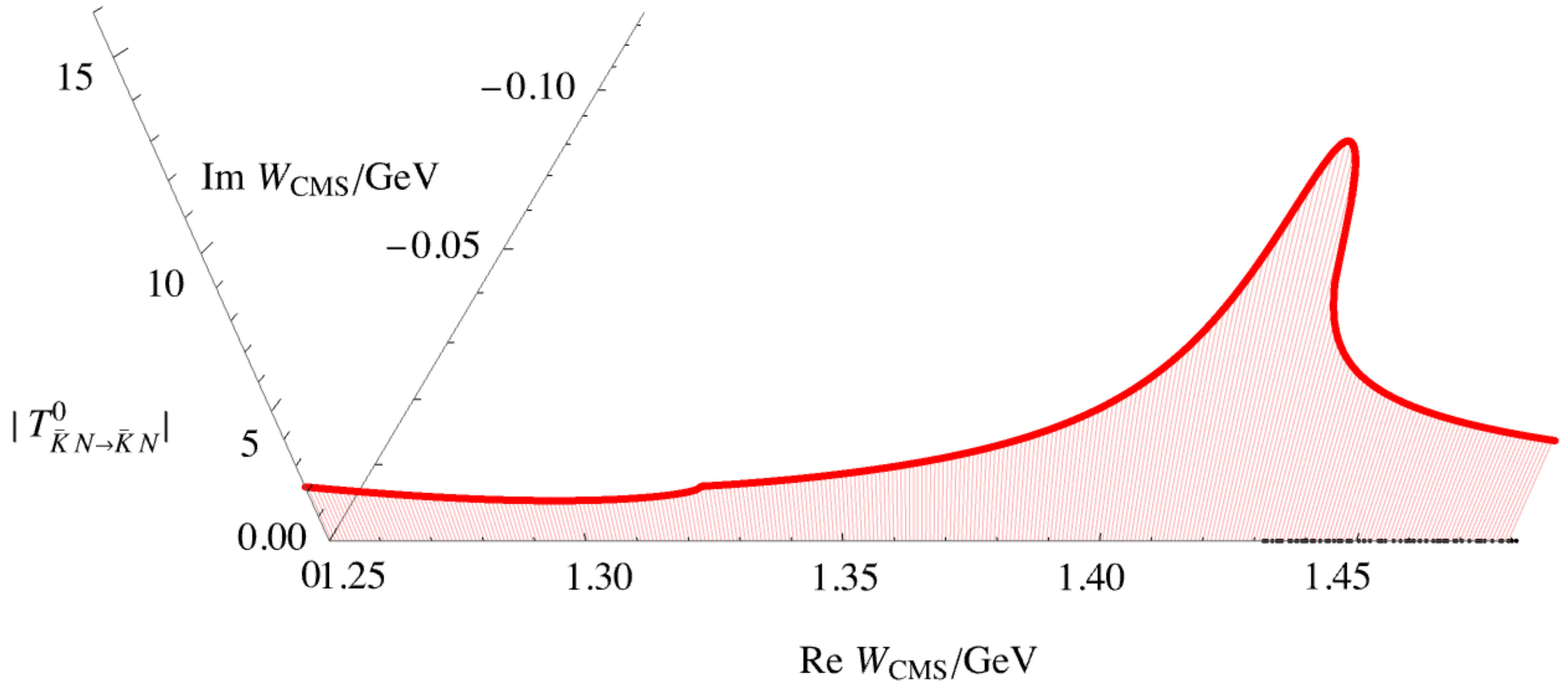

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S-matrix principles

analyticity, unitarity, Riemann sheets, …

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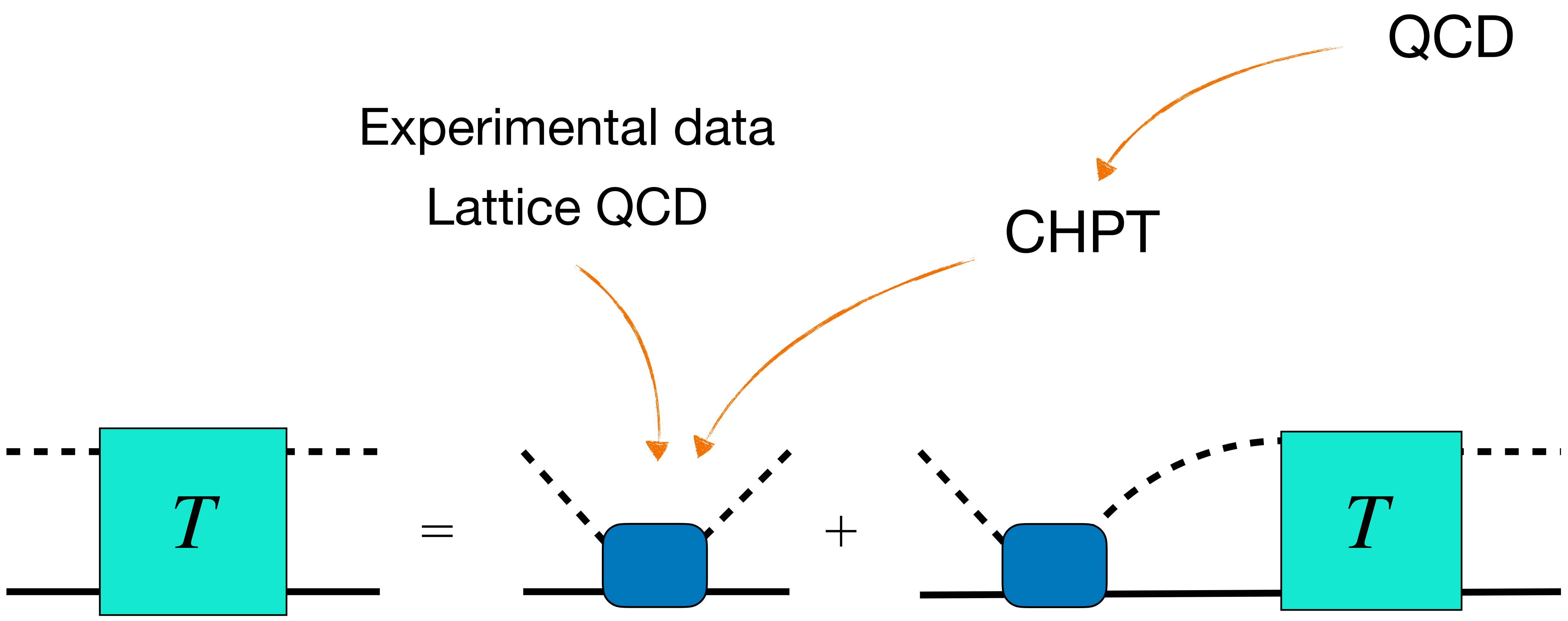

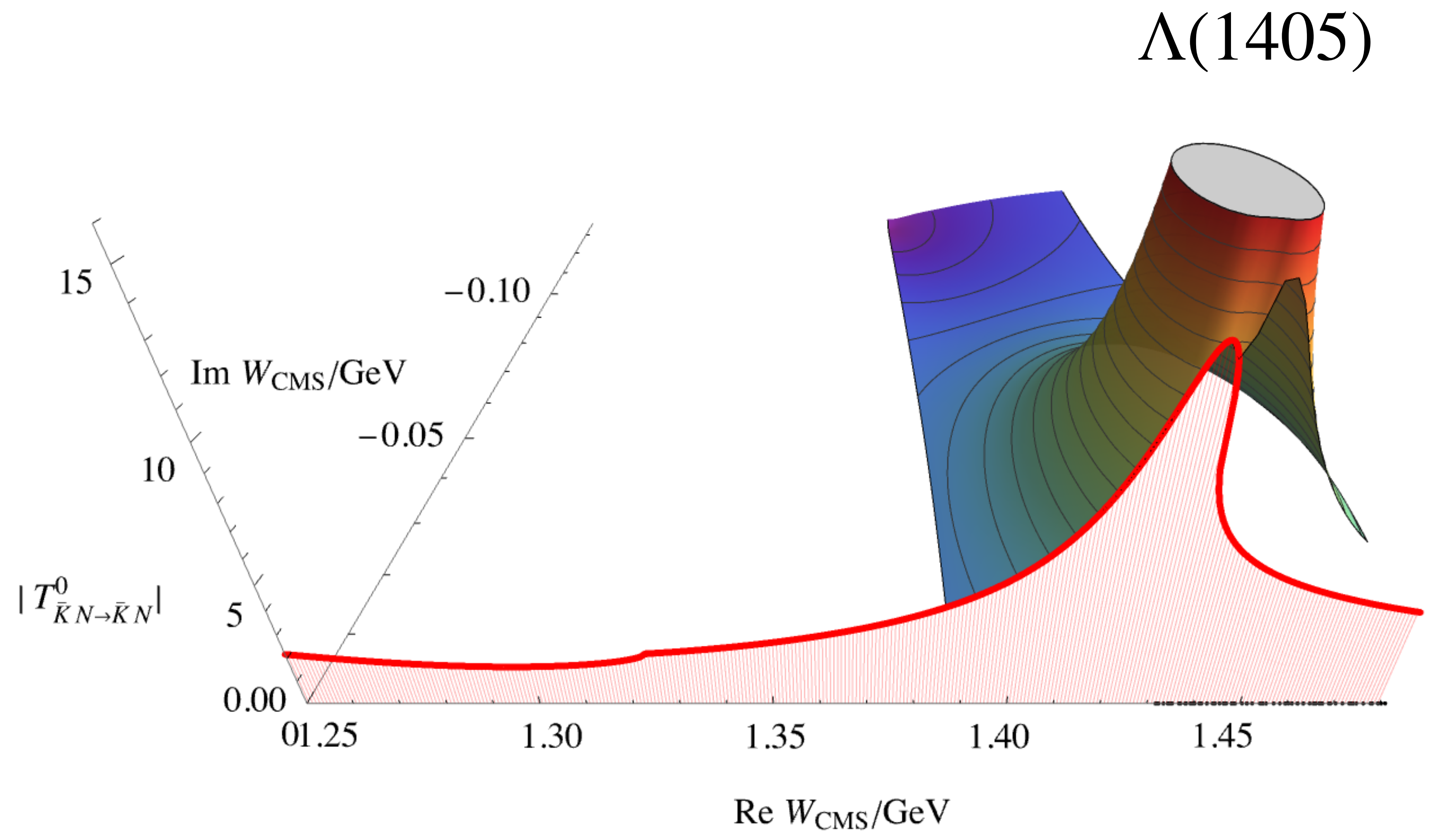

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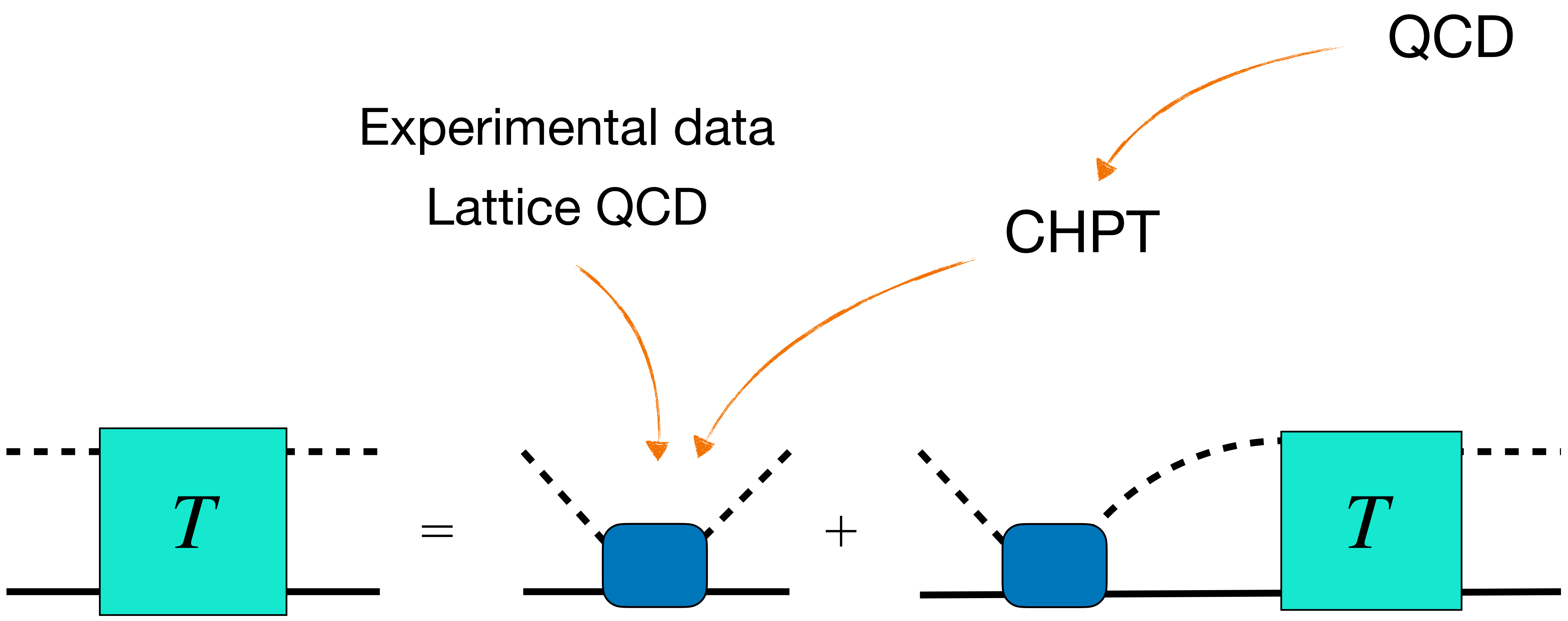

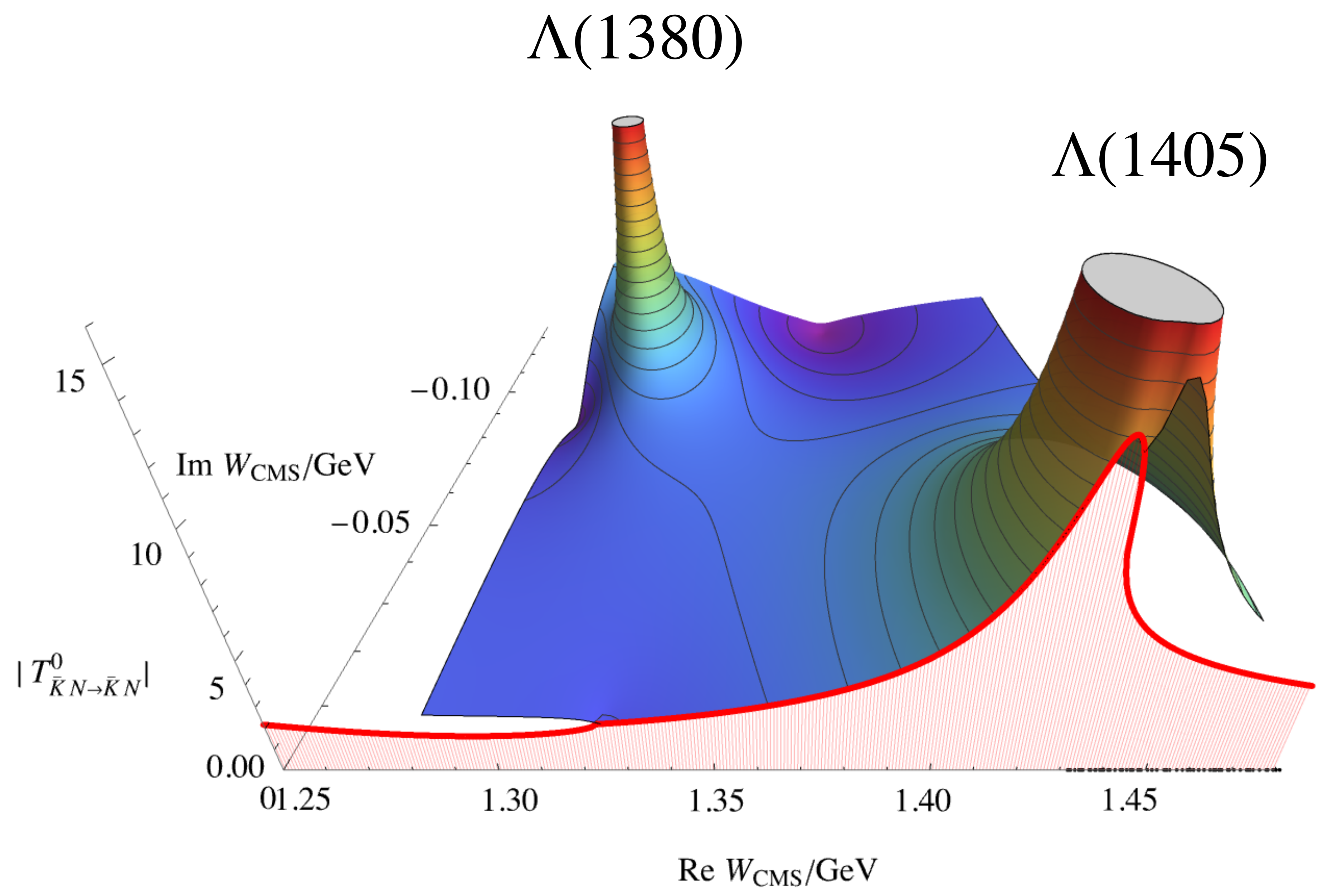

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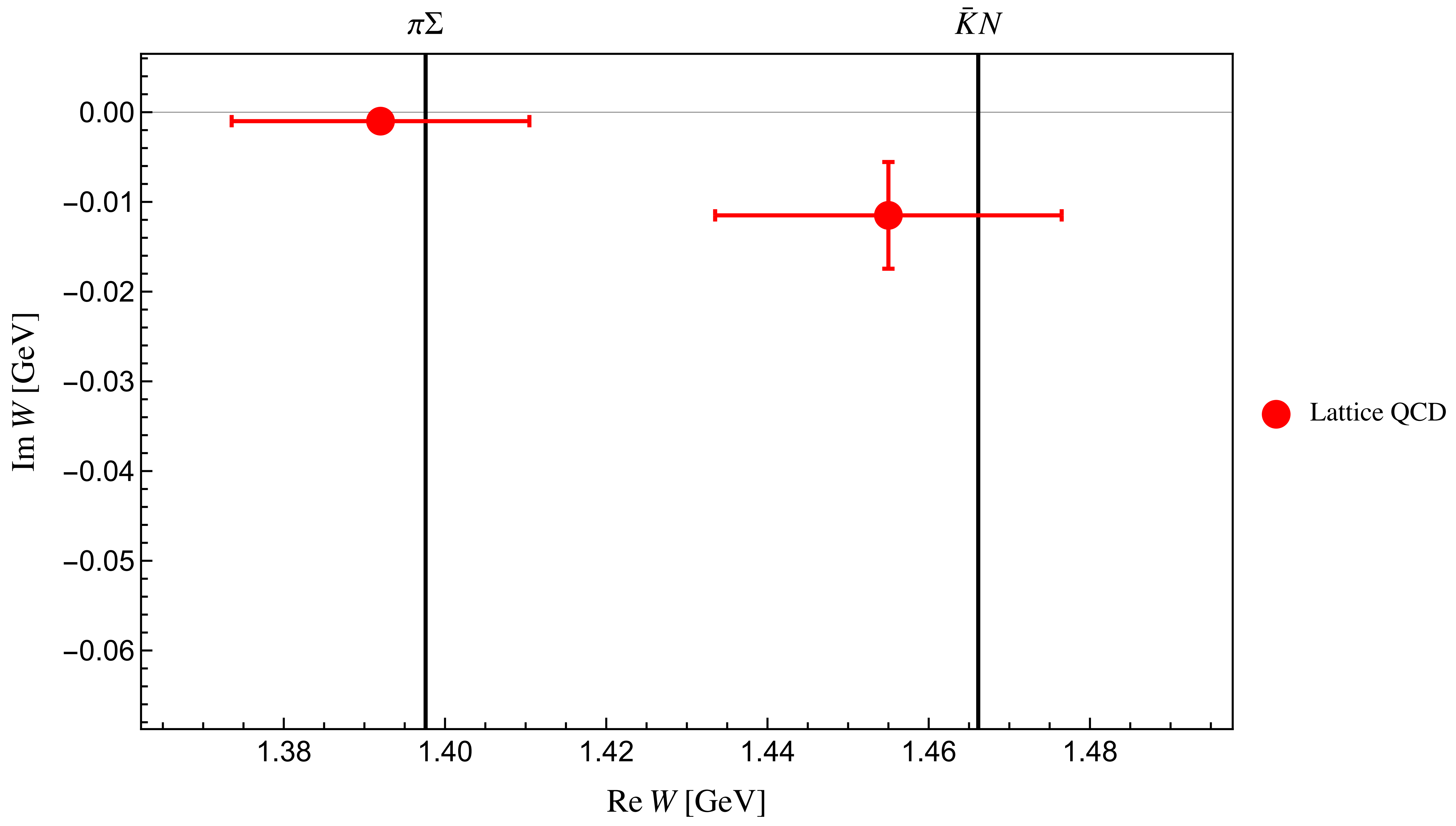
UNPHYSICAL QUARK MASSES

CHPT encodes quark mass dependence

- Available Lattice spectrum — BaSc setup[1]

$M_\pi \approx 200\,\text{MeV}\ \ M_K = \approx 487\,\text{MeV}$

$M_\pi L = 4.181(16)\quad a = 0.0633(4)(6)\,\text{fm}$



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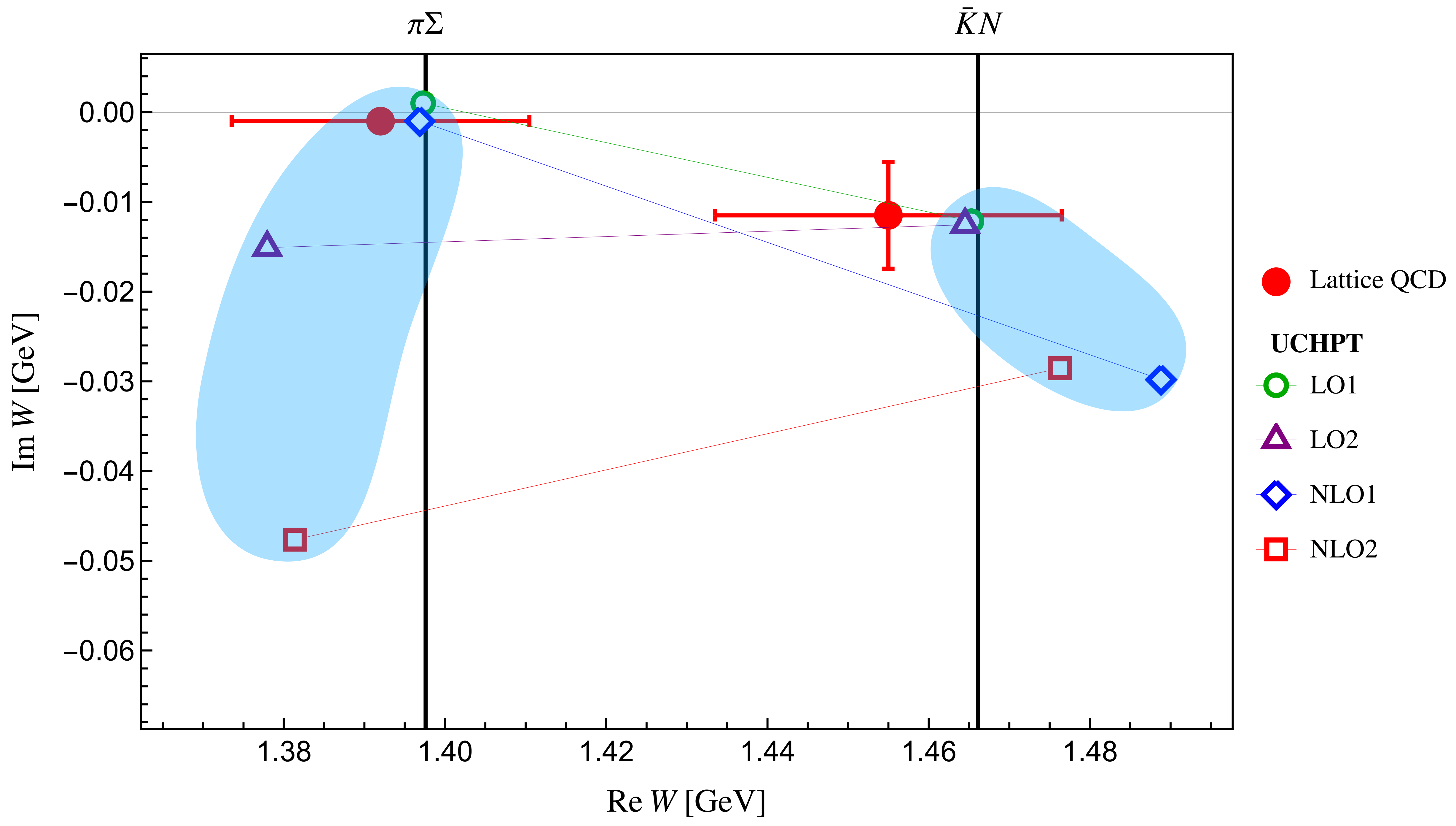
- Compare to prediction of UCHPT[2]



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- MM, Chris Culver, Andrei Alexandru, Michael Döring, Frank X. Lee Phys.Rev.D 100 (2019) 11
- Dehua Guo, Raquel Molina, Andrei Alexandru, MM, Michael Döring Phys.Rev.D 98 (2018) 1
- Michael Döring, Bin Hu, MM Phys.Lett.B 782 (2018) 785-793
- Neramballi Ripunjay Acharya, Feng-Kun Guo, Maxim Mai, Ulf-G. Meißner Phys.Rev.D 92 (2015) 054023

RESONANT AMPLITUDE

Chiral perturbation theory

Perturbative expansion of QCD Green's functions small momenta/masses of new DOF (π, K, η)

👍 well-defined QFT, power counting $T^{I\ell} = T_2^{I\ell} + T_4^{I\ell} + \ldots$

👎 no resonances!

Analytic tools[1]

S-matrix, dispersion relations, continued fraction,…

👍 data driven

👎 no direct connection to theory (channel-by-channel)

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Inverse Amplitude Method[2]

👍 restoration of S-matrix properties (Unitarity/Crossing)

- cross-channel $f_0(500), \rho(770), f_0(980), \kappa(800), K*(892)$
- connection to QCD (Nc/CP/quark mass - dependence)

👎 model dependence (regularisation)

$$T^{I\ell}_{IAM} = \frac{(T_2^{I\ell})^2}{T_4^{I\ell} + T_2^{I\ell}}$$

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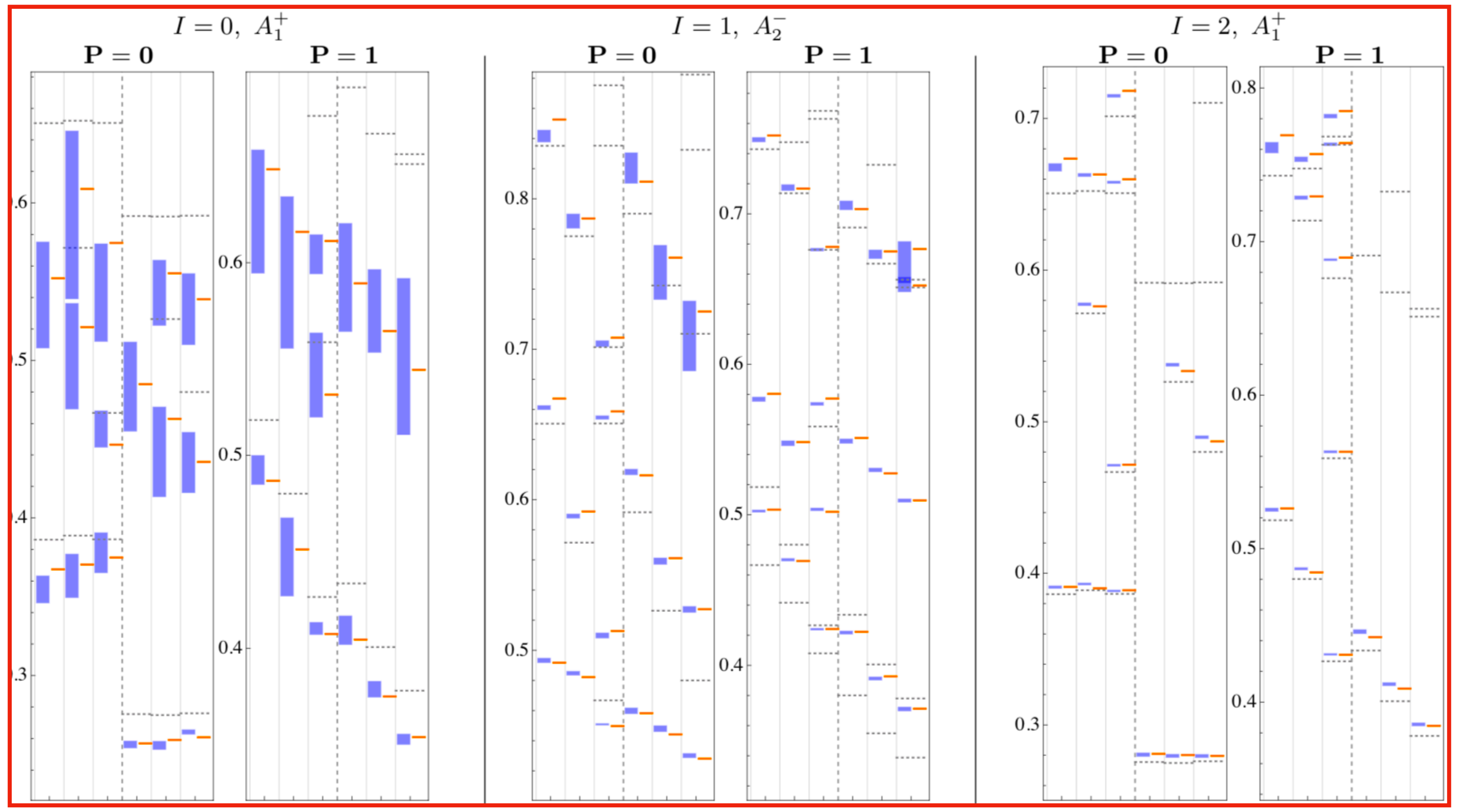
APPLICATIONS



GWQCD Finite-volume spectrum: Guo et al. (2016,2018) Culver et al. (2019)
$M_\pi = 224{,}315\,\mathrm{MeV} \quad L \lesssim 4\,\mathrm{fm}$

Cross-channel $\pi\pi$ scattering $(I = 0,1,2)$

- interpretation of LQCD results[1]
- resonance trajectories[2]
- $\pi\pi\pi$ amplitudes[3]

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[3] MM/Döring/Alexandru/Lee/Culver/Sadasivan Phys.Rev.Lett. 127 (2021) 22

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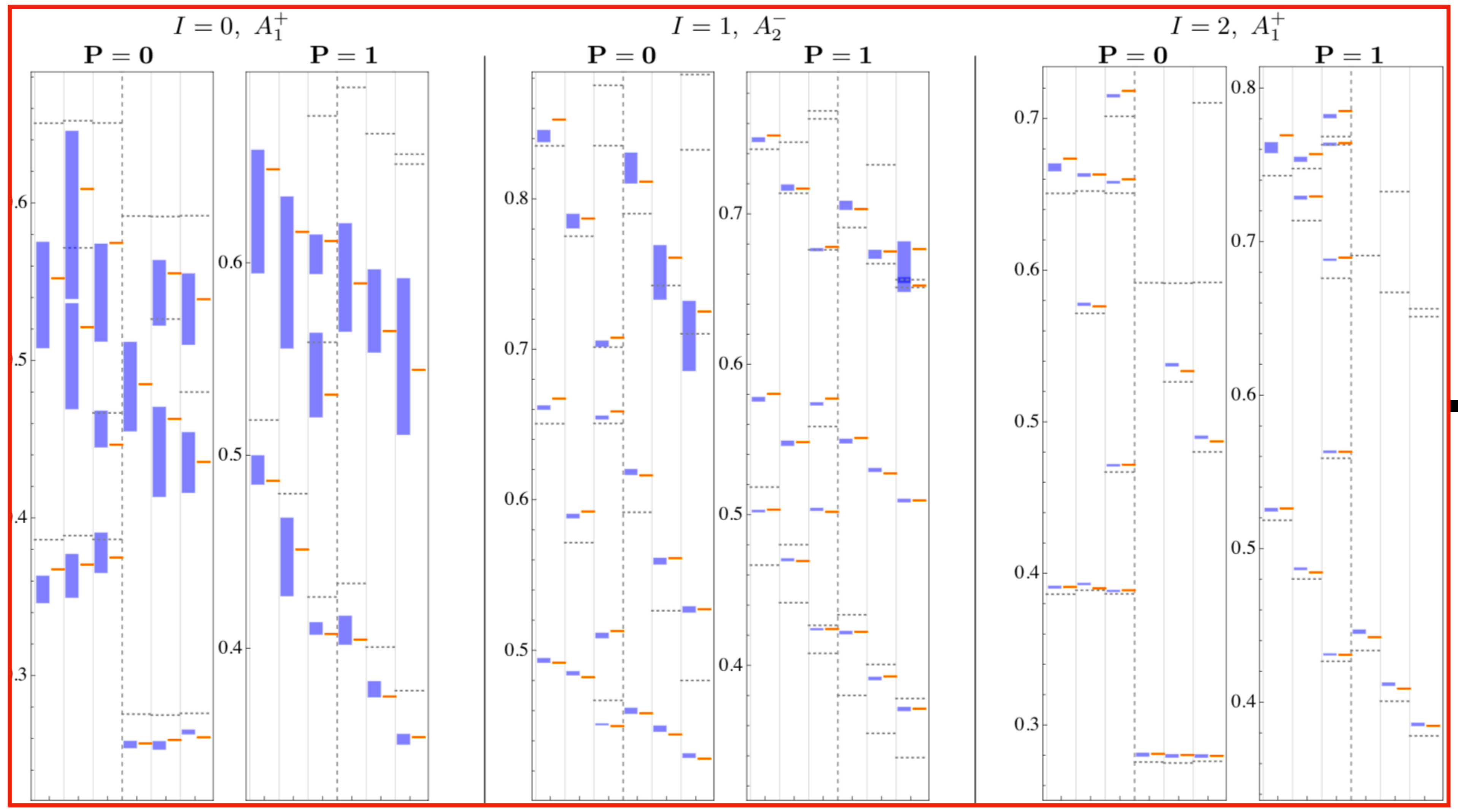

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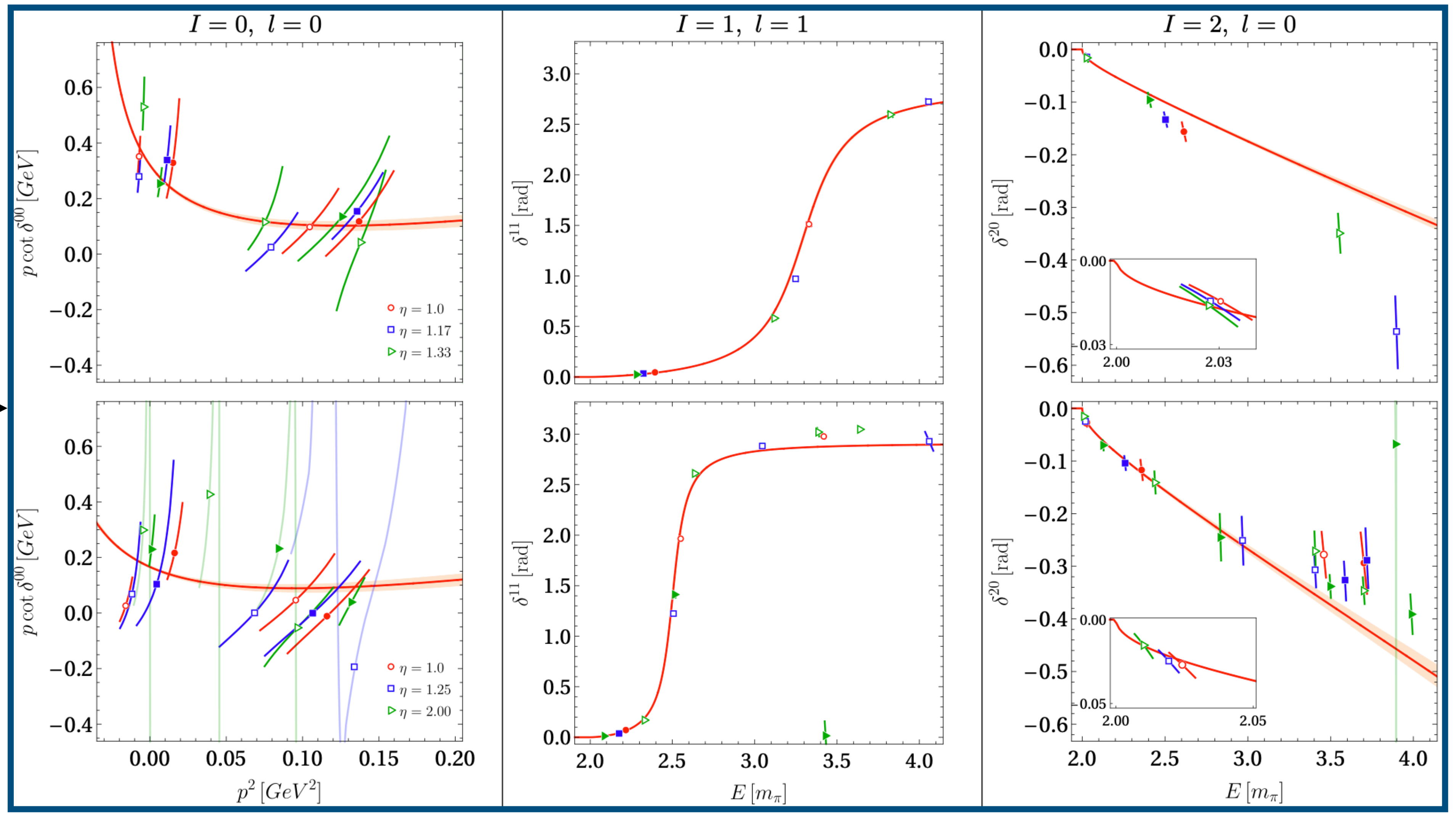

Phase-shifts in heavy universe (IAM+Lüscher's method)
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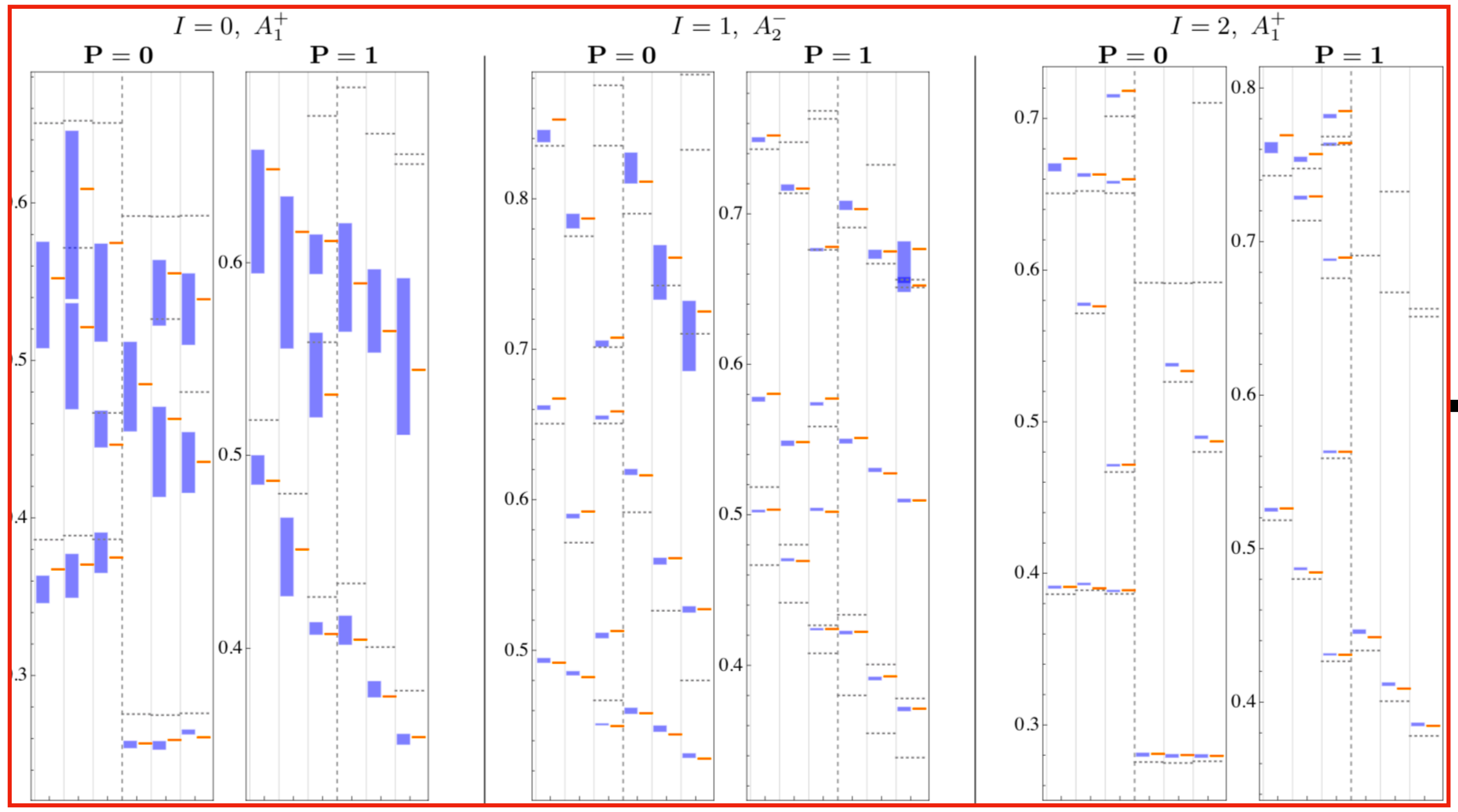

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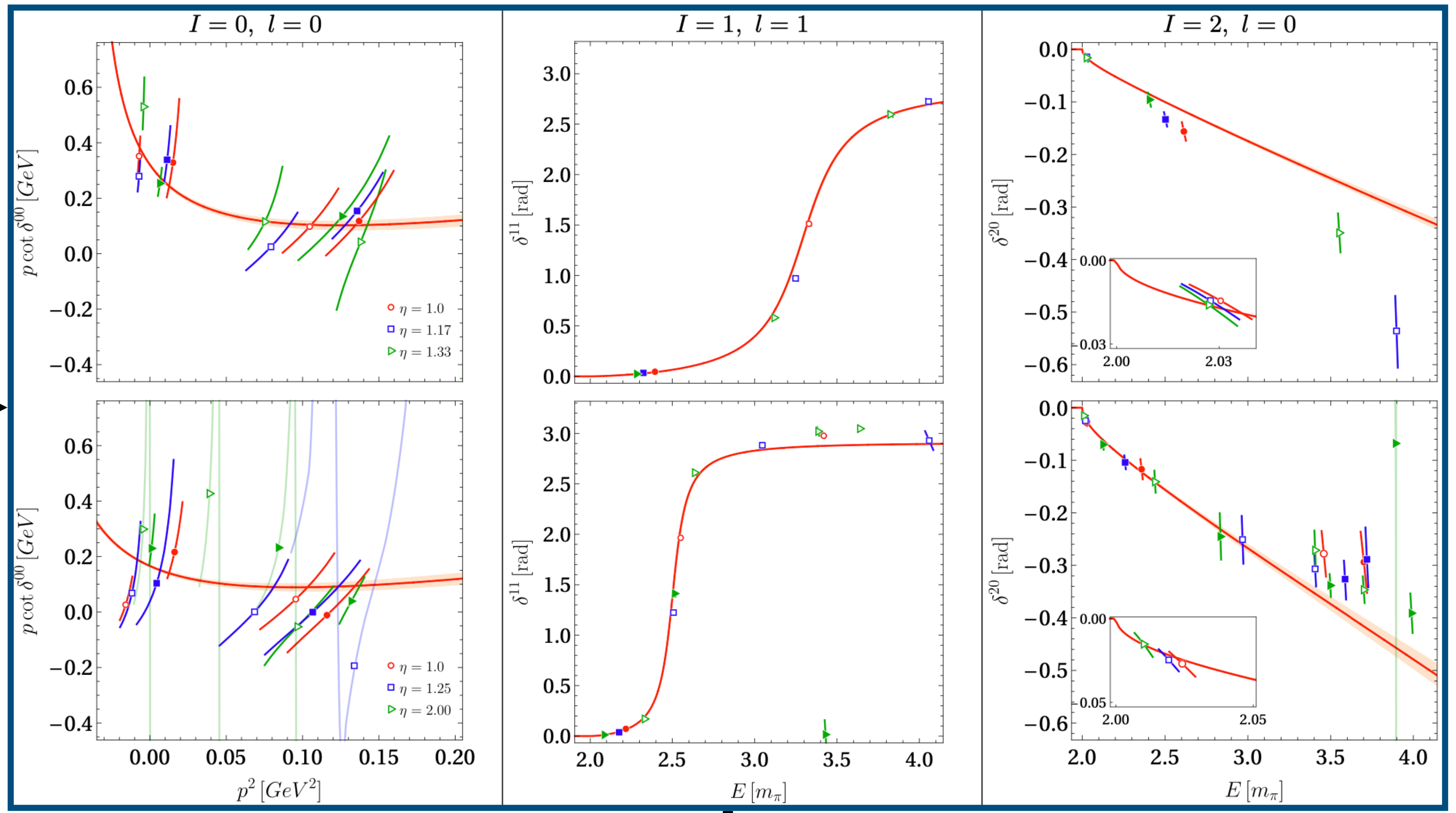

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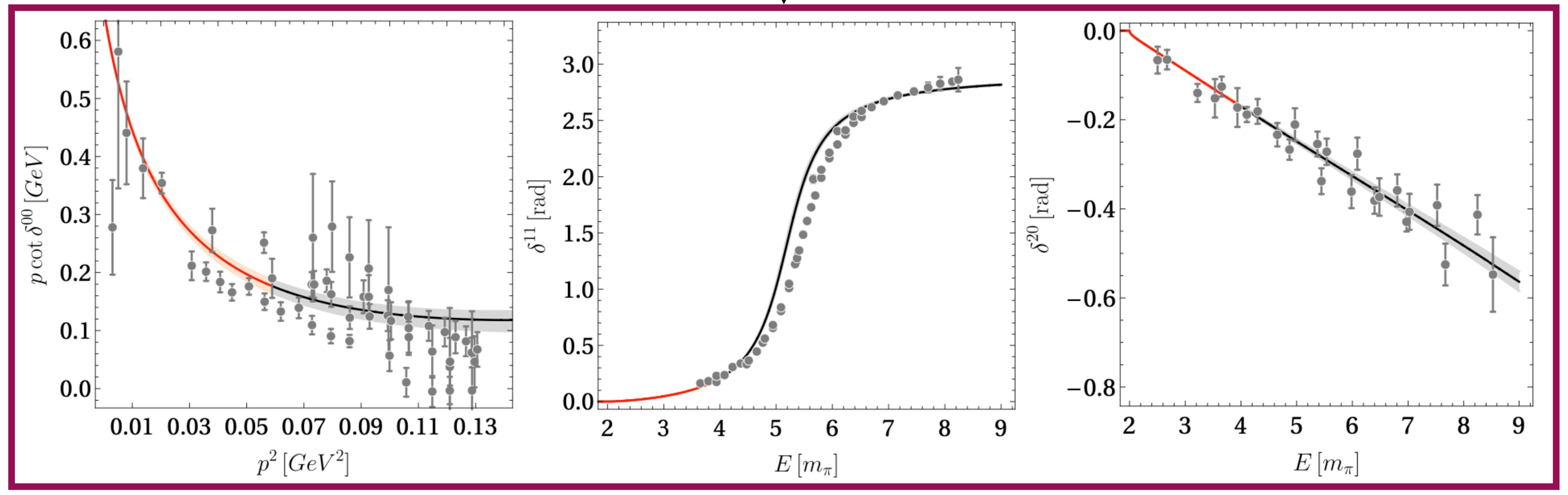
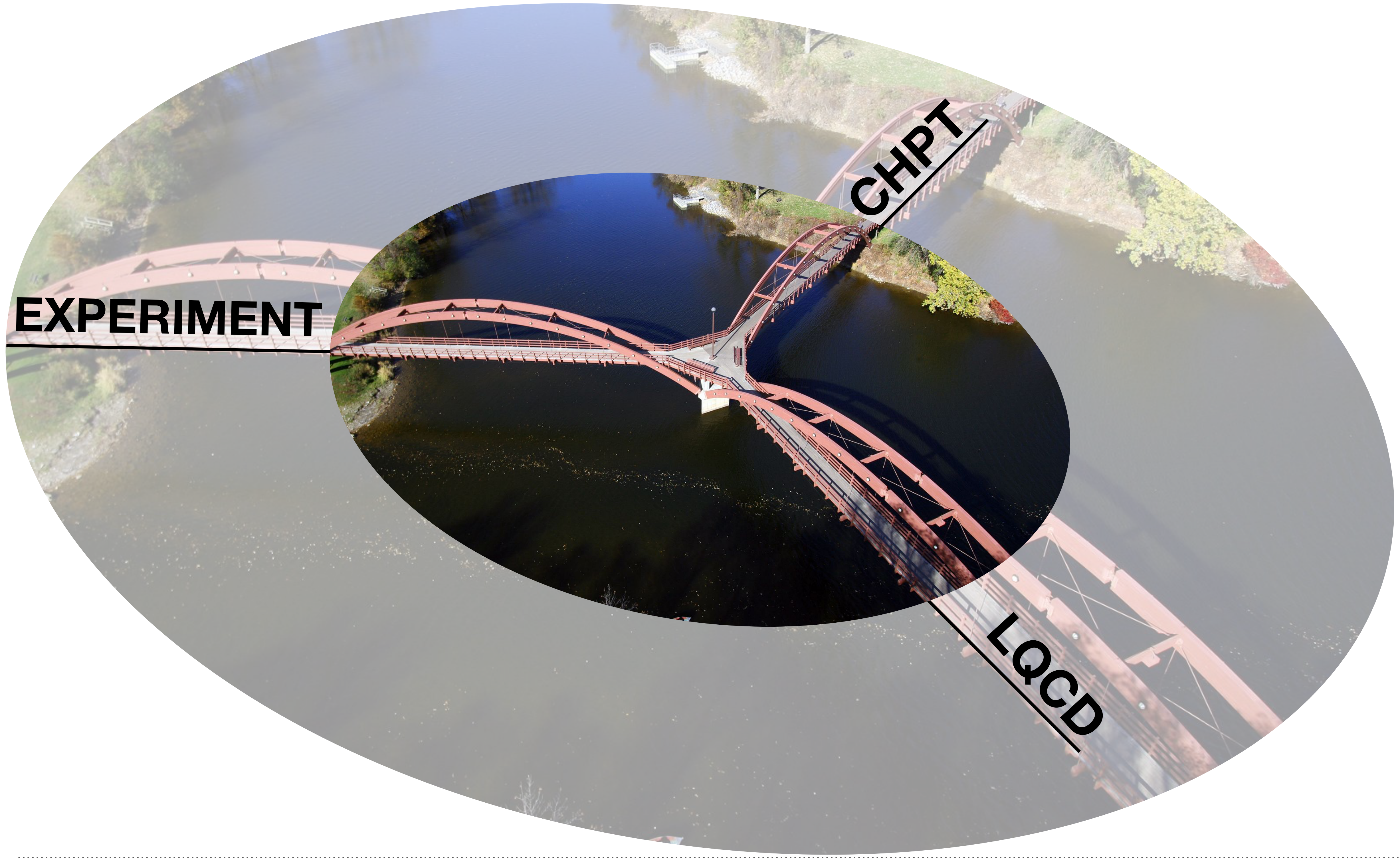


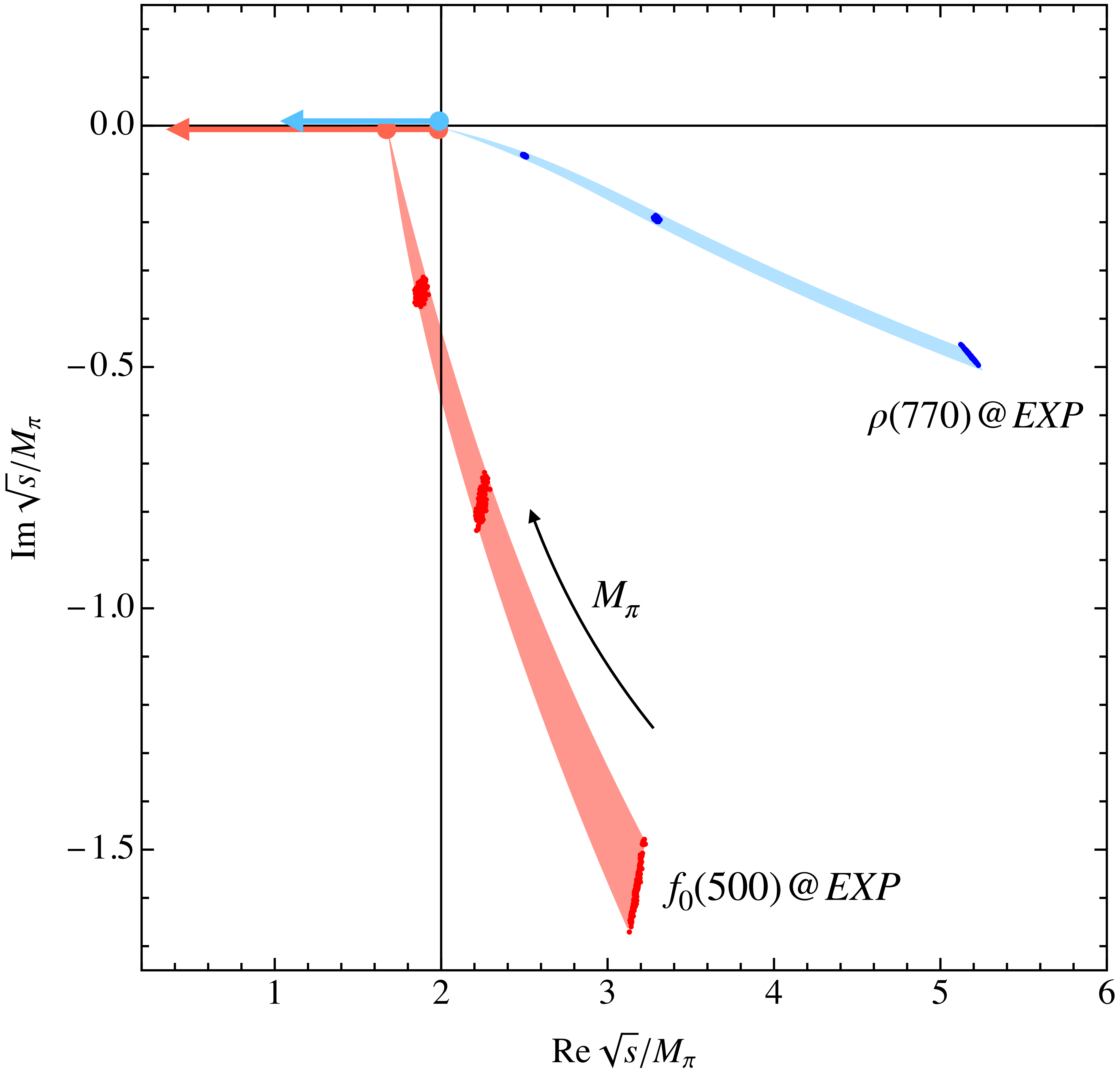
Chiral extrapolation to our universe
$M_\pi = 135\,\mathrm{MeV} \quad L = \infty$
No-fit comparison with experimental data[4]

[1] NPLQCD; HadSpec; ETMC; GWQCD; CP-PACS;….
[2] MM/Culver/Döring/Alexandru/Lee/Brett *Phys.Rev.D* 100 (2019) 11
[3] MM/Döring/Alexandru/Lee/Culver/Sadasivan Phys.Rev.Lett. 127 (2021) 22

Deeper insights into the structure of resonances

- $\rho(770)$ bound state for $M_\pi \gtrsim 450\,\text{MeV}$
- $f_0(500)$ bound state for $M_\pi \gtrsim 350\,\text{MeV}$





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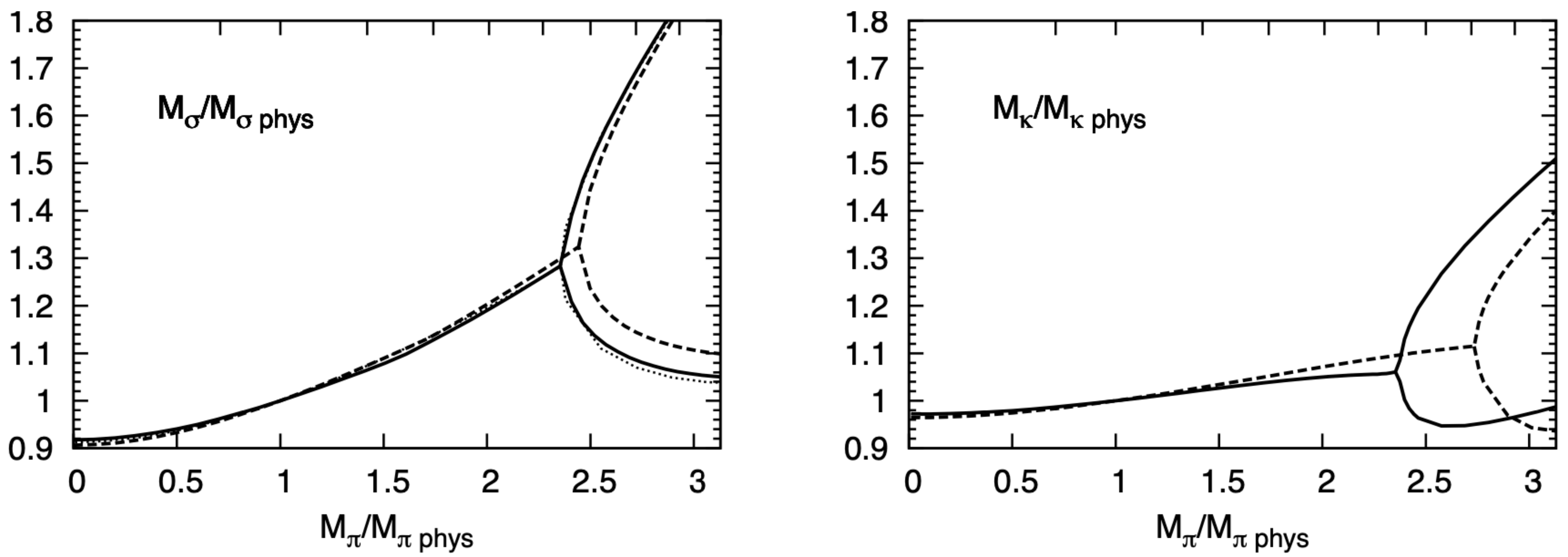
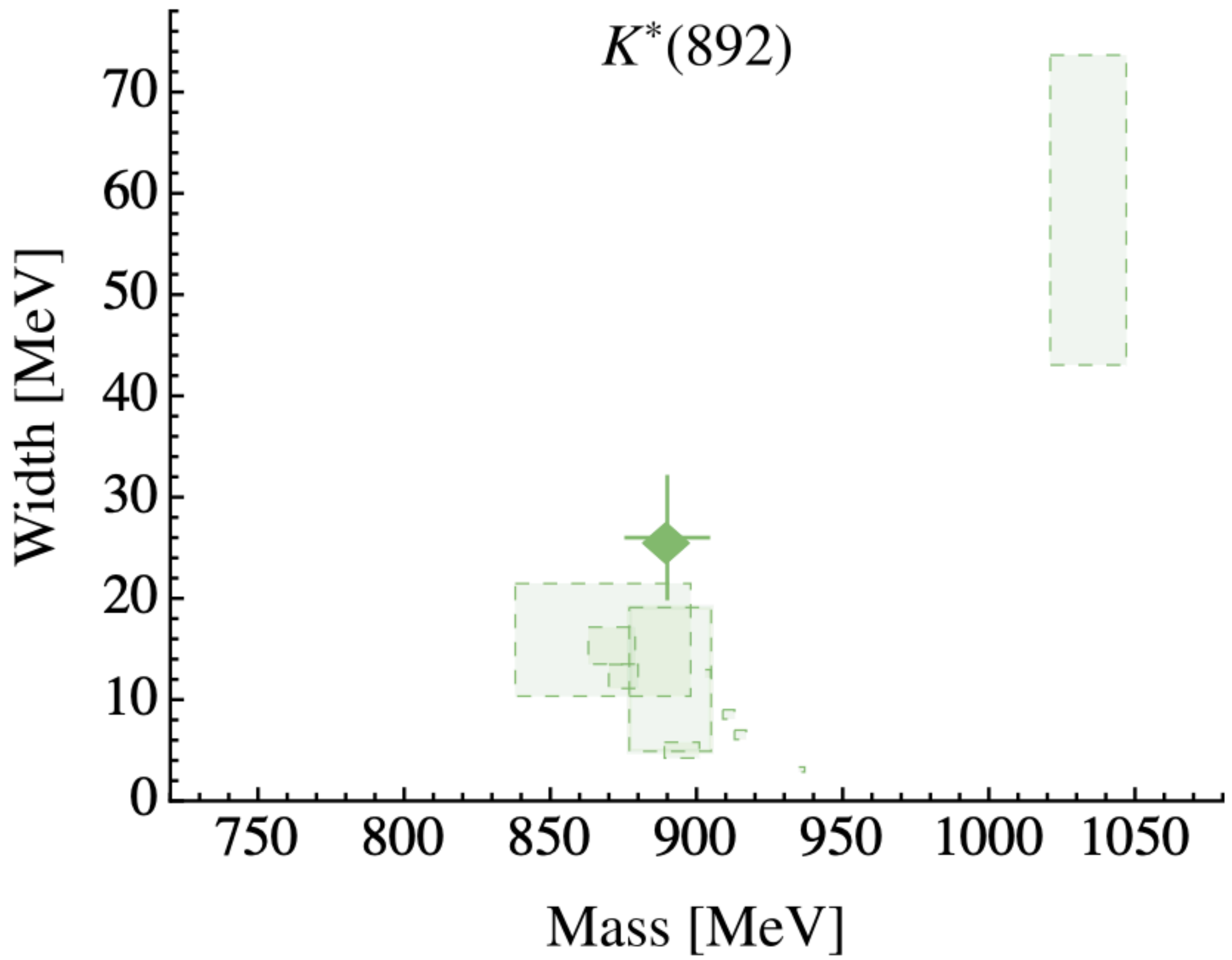
Strangeness mesons

- EFT/Unitarity based studies exist[1]
  - similar behaviour:

$$f_0(500) \leftrightarrow \kappa(800), \rho(770) \leftrightarrow K*(892)$$

- **Challenges**
  - More unknowns
  - Less data (LQCD[2] & Experiment)





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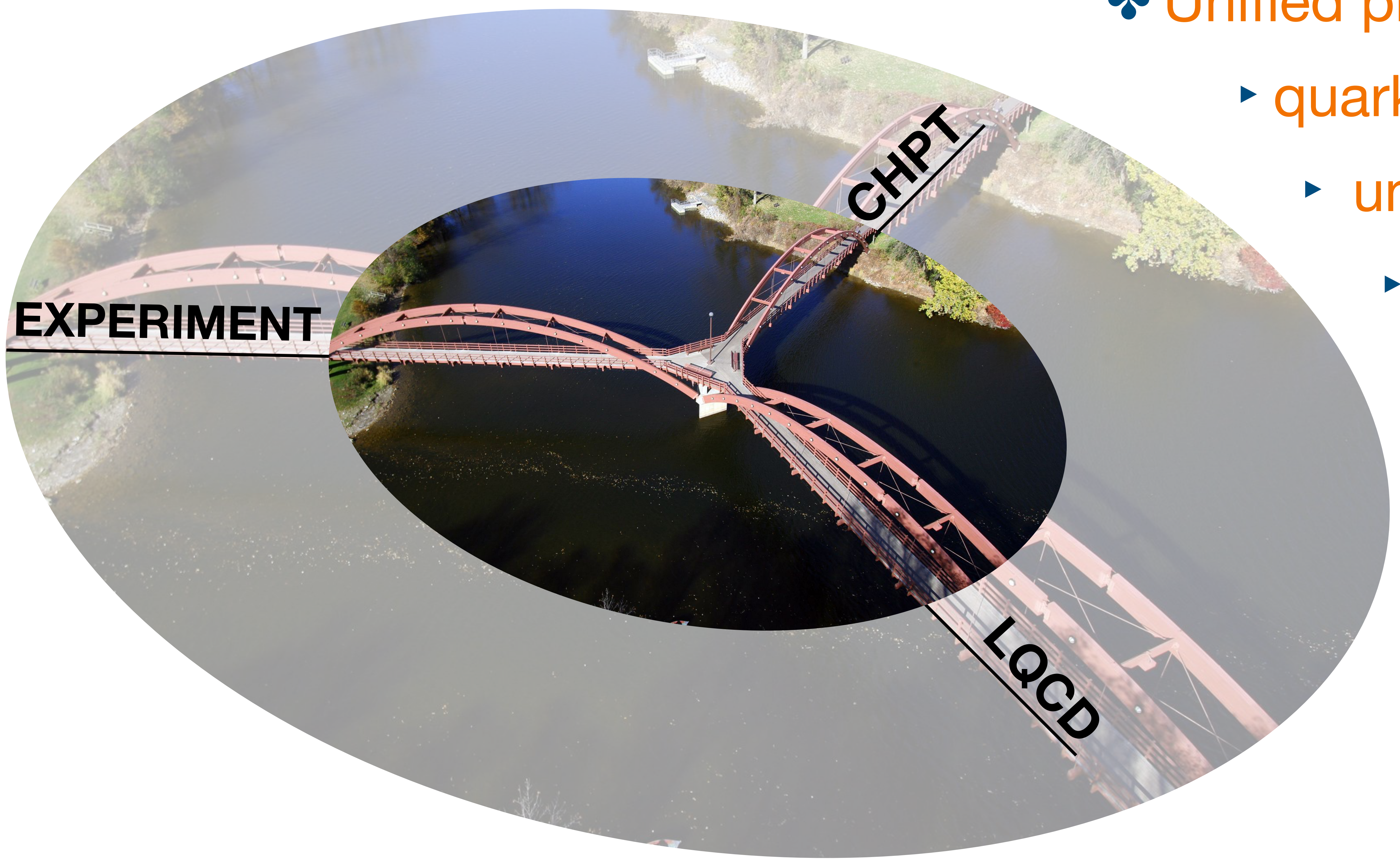
SUMMARY



- Synergetic approach to hadron resonances through

  Phenomenology + Lattice QCD + Effective Field Theories
- Unified pictures of resonances
  - quark mass behaviour
    - unified cross-channel studies
      - predictive power

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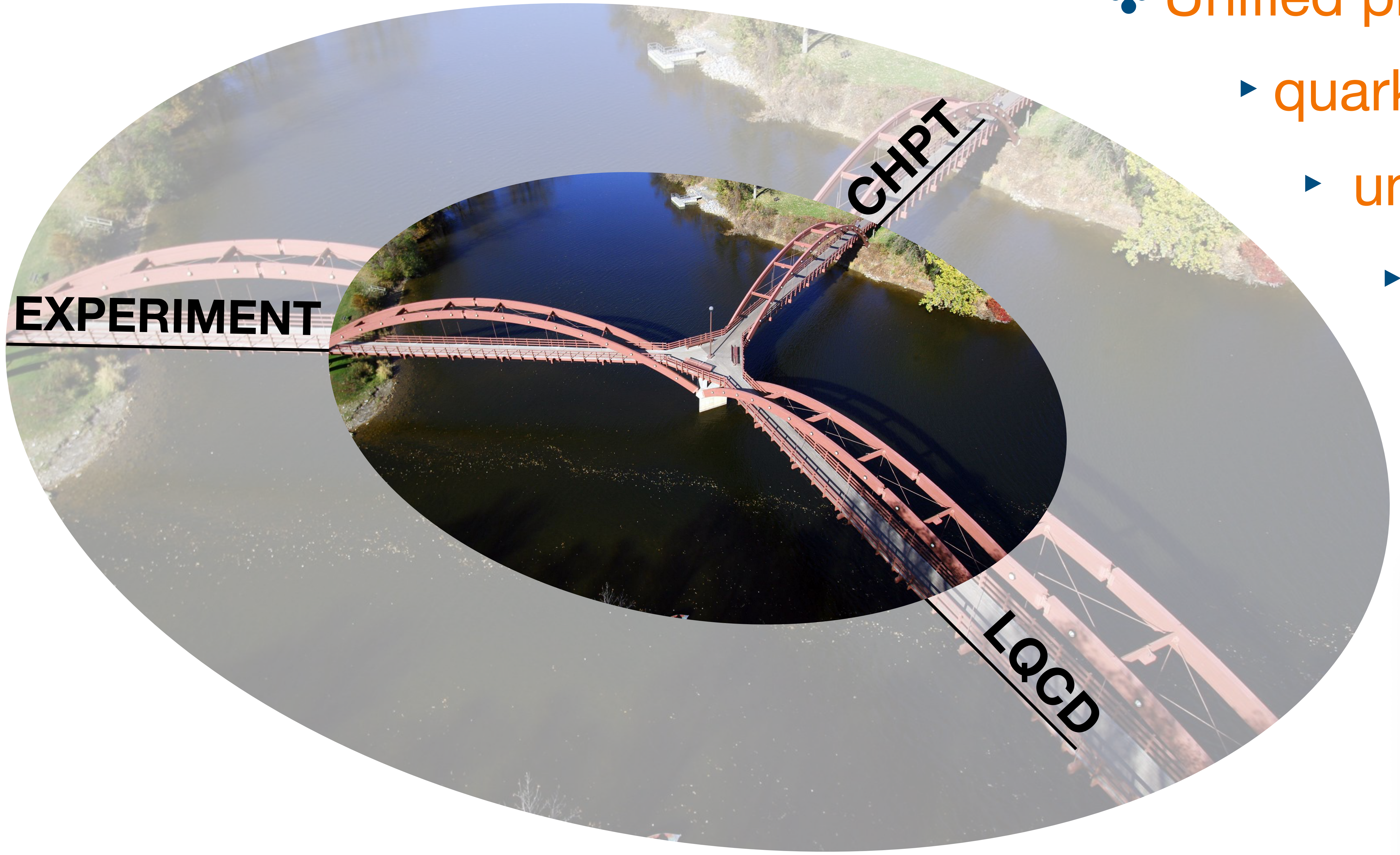

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Magic wand wishes

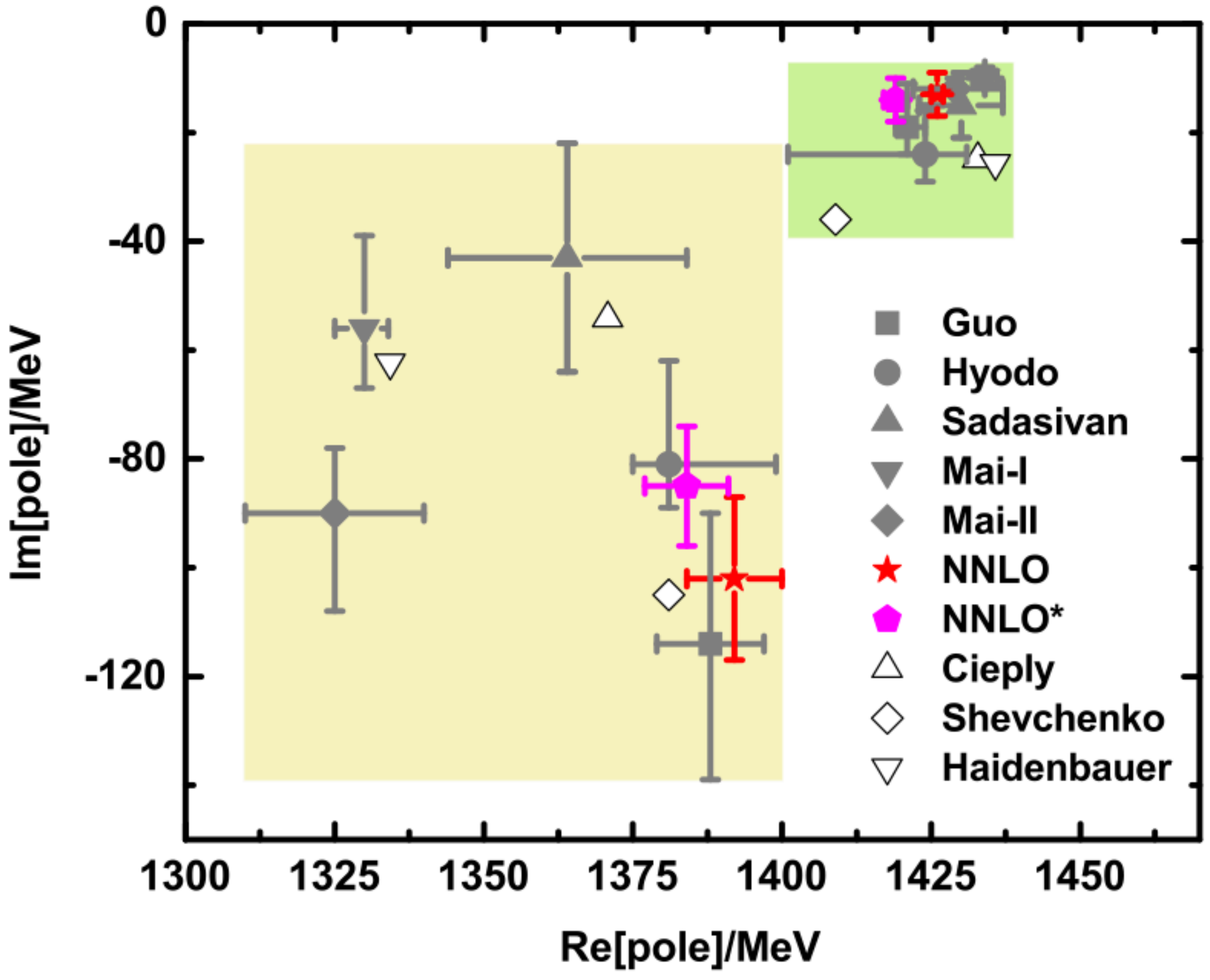
✨ more precise LQCD studies (+ systematics)

✨ unified $S = 0, \pm 1, \pm 2, ...$ theory

✨ Stronger experimental constraints

Chiral unitary approach[1]

- Chiral Perturbation Theory (#QCD#EFT)
  - form of the interaction at low energies
- Unitary amplitude from the Bethe-Salpeter equation
  - Fit free parameters to experimental data / LQCD
  - Record complex pole-positions
  - Many states can be explained[2]



[3] Fig: NNLO UCHPT Lu/Geng/MM/Döring Phys.Rev.Lett. 130 (2023) 7

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CHPT encodes quark mass dependence

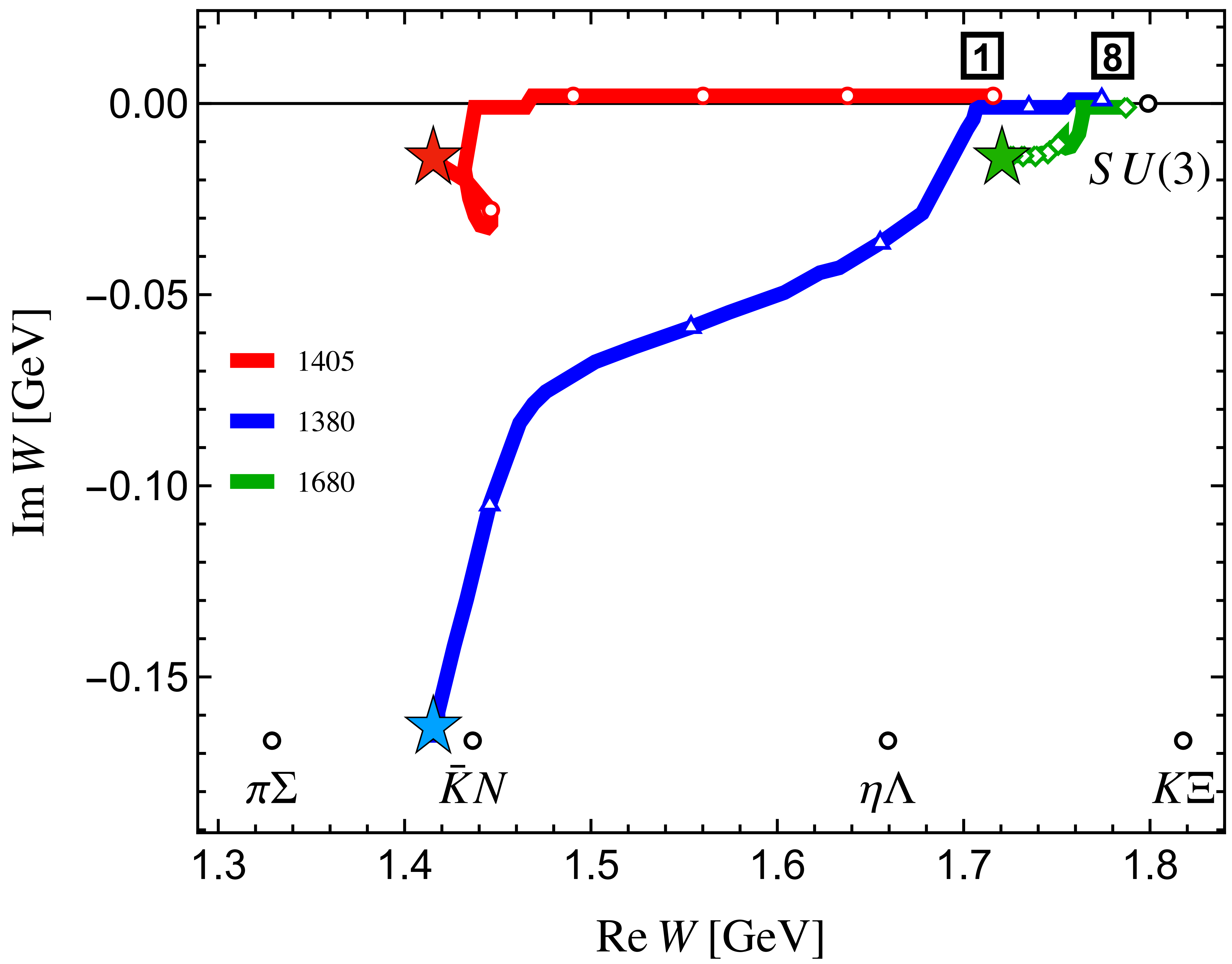
- SU(3) limit provides a simpler resonance structure[1]

  → 1 singlet + 2 octet poles

  → LO/NLO "tracks" differ[2]

- Resonance ⇜⇝ virtual bound state ⇜⇝ bound state

  (?) Lattice QCD



[1] Jido et al. Nucl.Phys.A 725 (2003); Garcia-Recio/Lutz/Nieves *Phys.Lett.B* 582 (2004) 49-54;
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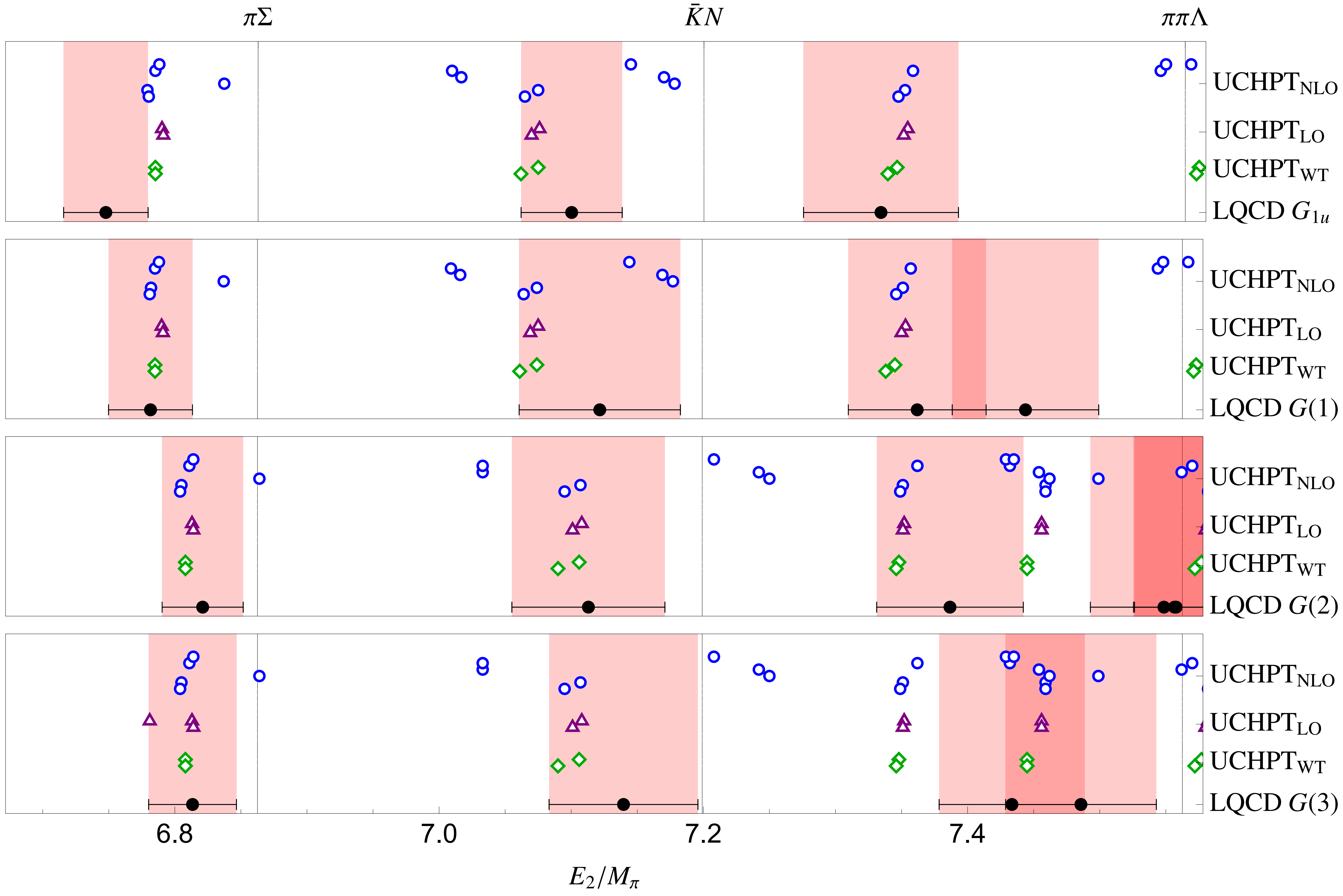
- Unified analysis[2] LQCD+UCHPT+EXPERIMENT[2]

  … mostly ok, but not always

  … what's about Hyperons?[3]

preliminary



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